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The transport and deposition of airborne debris from the Chernobyl nuclear power plant accident with special emphasis on the consequences to the United Kingdom

by F. B. SMITH, Ph.D. and M. J. CLARK, Ph.D.

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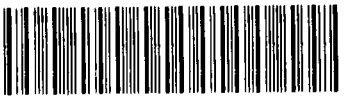
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LONDON, METEOROLOGICAL OFFICE.
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Addendum

Just prior going to press, measurements of the deposition of radioactivity commissioned by the Scottish Office revealed high values in a strip of the Scottish Highlands running north from Loch Rannoch. The location of this strip is consistent with the area of rainfall ≥ 5 mm shown in Figure 32, which fell mainly during the evening of Friday, 2 May. However our analysis of plume movement, based in part on, and consistent with, available radiological data, gave inadequate concentrations of airborne caesium at that time over the Highlands to explain these high depositions (see Figures 17 and 39). Possible explanations for this anomaly are being explored.

The transport and deposition of airborne debris from the Chernobyl nuclear power plant accident with special emphasis on the consequences to the United Kingdom

by F. B. Smith, Ph.D. and M. J. Clark*, Ph.D.

SUMMARY

This paper gives a description of the fate of the radioactivity that escaped from the wrecked reactor at Chernobyl for 10 days and spread over most of Europe. Part of the debris crossed Britain a week after it was emitted, and much of it was deposited on upland areas in the north-west. Much has been learned about the behaviour of the debris, and a discussion of this knowledge is included.

1. THE ACCIDENT AT CHERNOBYL

The USSR has a large nuclear power programme. One of the reactor designs commonly employed is a graphite moderated, water-cooled system with the initials RBMK. In early 1986 four such RBMK reactors were in operation at the V.I. Lenin Nuclear Power Station at Chernobyl in the Ukraine, and two others were under construction on the site. The destruction of Reactor 4 resulted in the world's most serious accidental release of radioactive materials into the atmosphere since nuclear power generation began.

The accident which occurred on 26 April 1986 did not occur during normal operation of the reactor. In spite of inherent weaknesses in the RBMK character and design (which were pointed out by western experts over 10 years ago), reactors of this type had operated safely and successfully for many years in the Soviet Union. Instead, the accident occurred during a rather special experiment to test a safety system when the reactor was under the ultimate control of an electrical engineer rather than a senior reactor controller. Details of the events leading up to the disaster have been described in detail elsewhere (Gittus *et al.* 1987) and only a brief summary will be given here. The object of the experiment was to see if the mechanical inertia of rotation of the turbines could generate sufficient electricity to keep vital parts (like pumps) within the reactor working for 50 seconds following a sudden cut-off of both the driving steam from the reactor and the supply of electricity from the grid. The experiment assumed that stand-by diesel generators could be started and take over the generation of electricity for these vital parts within at most 50 seconds.

To perform the experiment, the plan required power to be reduced to 25% of normal. Reduction started at 0100 h on Friday, 25 April. By 1305 h the power had been halved and one of the two turbine generators was switched off. Soon afterwards, because of the requirements of the national grid supply, further reductions in power were delayed until 2310 h when the reduction was resumed. However, owing to an error, the power was allowed to fall briefly to about 1% of full power, well below the level of 20% at which the RBMK reactors are known to be potentially unstable. One cause of this drop in power was xenon-135 (Xe-135) poisoning of the core, produced by a decay chain process from other fission products. At high power the Xe-135 is rapidly destroyed by neutrons produced by

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fission, but at low power insuffient neutrons are available to balance its generation. Since the Xe-135 is a very effective absorber of neutrons, it made it very difficult to control the reactor and increase power significantly.

By 0100 h on the following morning (26 April), power was restored to a quasi-stable level of about 7%, still well below the safety level of 20% for real stability. To do this the operator had to withdraw the control rods further out from the core than was normally permitted or safe.

At 0103 h it was noted that the water flow in the core was too high. Consequently, little steam was being generated and, because water absorbs neutrons better than steam, power began to drop again. The operator therefore withdrew the control rods even further, and with so much water in the core the amount in the steam drums dropped, so that the operator decided to increase the water levels. In the core, the water hardly heated up at all as it passed through, although overall the water temperature was rising gradually to just below boiling point.

At 0122 h, with the reactor deceptively stable, the experiment was started. The operator disconnected the 'trip' which should have automatically shut down the reactor once the test was under way (and would in the event have saved the reactor). The apparent reason was to be able to repeat the experiment if so required.

At 0123 h 04 s the steam supply was cut to the remaining generator. As it slowed down, the coolant pumps also slowed down and the water coolant (initially just below boiling) started to boil. Because of a 'positive void coefficient' the power started to rise as more steam was generated. This was an accelerating process and the power rose faster until instability set in at about 0123 h 31 s.

At 0123 h 40 s the operator tried to reintroduce the control rods but they moved too slowly, and it was too late.

Four seconds later the power reached 100 times normal power. The fuel rods probably fragmented and a rapid and highly explosive rise in steam pressure resulted, lifting the enormous reactor top shield. The core was now exposed to the air and rapid chemical reactions probably took place causing a second explosion and destroying the building. Burning graphite and core debris were consequently spewed out over the site and into the atmosphere.

Since the reactor had been operating continuously for well over 2 years, the core content was rich in a wide range of fission products. Many of these were highly radioactive. The radioactivity, or the rate at which these various products transform to form other products, is measured in units of disintegrations per second, or becquerels (Bq). Roughly 2×10^{18} Bq of activity escaped in the following 10 days, of which about a third was released on the first day (see Figure 1). Noble gases and volatile fission products were released in quantity including two isotopes which were to pose a threat to health over much of Europe, namely iodine-131 (I-131) and caesium-137 (Cs-137). Activation products such as caesium-134 (Cs-134) were also released.

Two people died immediately and 29 others died shortly afterwards as a result of severe radiation injuries incurred trying to contain the accident, whilst some 200 other people, mainly station personnel, sustained serious injuries resulting from being exposed to very high levels of radiation.

2. THE INITIAL RELEASE

Most of the material which became airborne would have risen due to the intense heat associated with the very large quantities of energy released during the explosion.

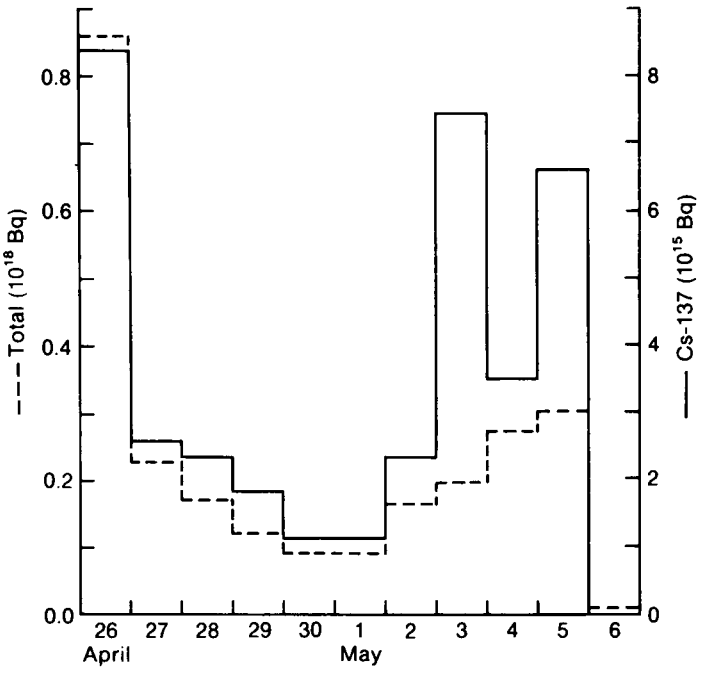


FIGURE 1. Daily emissions from Chernobyl following the accident on 26 April, according to the Soviet Report to the International Atomic Energy Agency (1986), and reproduced from the paper by Persson *et al.* (1987).

Nevertheless some would be in the form of large particulates and would have fallen out due to gravity, to be deposited within a few kilometres of Chernobyl. This local loss makes the assessment of the total release on the first day somewhat tentative.

According to the Soviet Report to the International Atomic Energy Agency (IAEA 1986), the approximate emissions on this first day are as follows:

I-131	:	100–200 PBq
Cs-134	:	2–5 PBq
Cs-137	:	5–10 PBq
(1 PBq	=	10^{15} Bq)

The total release of all radioactive material was about 800 PBq with an uncertainty factor of about 2.

3. THE DURATION AND MAGNITUDE OF THE RELEASE

Enormous efforts, not to mention courage, were expended to contain the release of radioactive material to the atmosphere and to ground waters. About 5000 tonnes of boron carbide, dolomite, sand, clay and lead were dumped on top of the reactor from helicopters. As a result, by day 5 the emissions had fallen by 90 per cent, but later rose again since the residual power of the fuel heated the debris to over 2000 °C, resulting in partial penetration

of the dumped covering material. By 5 May (day 10) emissions were up to a third of the level of day 1, 26 April. However, by the following day (6 May) workers had managed to cool the core by the injection of nitrogen and water, and emissions virtually ceased. Even so, small detectable traces were sensed in the atmosphere for at least another 3 months in Europe.

In some contrast to these early estimates of emission shown in Figure 1 are results of an analysis of radioactive fall-out within 400 km of Chernobyl reported by Izrael *et al.* (1987). The measured pattern of fall-out can be approximately related to time because of a systematic progression in wind direction over the first 5 days following the explosion. In this way an emission-time profile can be inferred from the contours of deposition. Izrael *et al.* (1987) give the following figures in which all numbers are percentages of the total 5-day release (excluding, it is believed, the significant contribution from the initial explosive release which rose to high altitudes).

Column	1	2	3	4	5
Sat.	26 April	32	17	10	9
Sun.	27 April	24	27	30	31
Mon.	28 April	19	29	40	42
Tue.	29 April	14	14	18	15
Wed.	30 April	11	13	2	3

Column 1 : day and date.
Column 2 : estimated relative releases of total radioactivity from airborne measurements, excluding radioactivity released in the initial explosion.
Column 3 : relative releases of γ-activity inferred from fall-out.
Column 4 : relative releases of Cs-137 inferred from fall-out.
Column 5 : relative releases of I-131 inferred from fall-out.

Finally in this section it is interesting to compare the magnitude of the emissions from Chernobyl with those from other accidental releases and from the weapon tests of the late 1950s and 1960s. These emissions are set out in Table I.

TABLE I. *Activity released (Bq) from Chernobyl compared with releases from weapon tests, from the 1957 Windscale accident and the Three Mile Island (TMI) accident*

Nuclide	Chernobyl	Weapon Tests	Windscale	TMI
Cs-137	3.7×10^{16}	1.5×10^{18}	4.4×10^{13}	Not detected
Cs-134	1.9×10^{16}	$<1.5 \times 10^{15}$	1.2×10^{12}	Not detected
I-131	6.7×10^{17}	7.8×10^{20}	5.9×10^{14}	7.4×10^{11}

4. DURING THE FIRST FEW DAYS

First recognition, outside the USSR, that a disaster had occurred came when automatic radiation monitoring instruments at Forsmark, a Swedish nuclear plant north of Stockholm, set off alarm signals on the morning of Monday, 28 April. After repeated questioning by the Swedish Ambassador in Moscow, the Soviet authorities released the first

details of the accident on the Monday evening. By Tuesday morning the Central Forecasting Office at Bracknell were calculating forward trajectories starting from Chernobyl using forecast winds calculated at the 850 mb pressure level. These trajectories suggested that whilst there was no immediate risk to the United Kingdom, there was a possibility that the plume might cross Britain by the end of the week. The word 'plume' will be used to denote the cloud of radioactivity from Chernobyl to distinguish it from meteorological clouds, even though the shape of the plume differed considerably from that of a classical plume from a chimney. However, questions abounded — Was the release continuing? How much was being released? What was the effective height of release? What winds should be used? Where had the plume got to? In these early days vague Press Reports were all that there was to go on, and this seriously hampered the prediction of the movement of the radioactive plume. It later became evident that widespread measurements were being made and, even though they were somewhat irregular, they proved invaluable in post-accident analyses.

Late on Wednesday, however, reports of elevated radiation levels measured at laboratories in northern Italy and in Monaco were received through the UK National Radiological Protection Board (NRPB). Although the precise time when these measurements were taken was not known, it became reasonably probable that the winds would carry the plume into Britain on the Friday (2 May), and this information was issued on Thursday morning by the Meteorological Office.

The Forecasters and Press Officers of the Meteorological Office were kept extraordinarily busy during this period presenting evidence to visiting TV film crews and answering numerous enquiries from laboratories, other Government departments, the media and the general public. Staff with specialized interests also became heavily involved and helped to meet the demand from the media for informed comment. Liaison between the Office and other Groups was generally good despite the enormous work-load suddenly thrust upon all concerned.

The NRPB was similarly inundated with enquiries from many quarters about the potential radiological hazard associated with the release from Chernobyl. There was enormous public interest in the consequences, particularly during the passage of the Chernobyl plume over the United Kingdom during 2–4 May 1986. The Board also acted as a focal point for receiving, collating and interpreting monitoring information from nuclear installations and other laboratories (Clark 1986), including data from overseas. Inevitably this work, coupled with the large public interest, placed a strain on basic communications (Dunster 1986) and on 7 May the Government set up enquiry points and a technical information centre at the Department of the Environment in London.

5. METEOROLOGICAL CONDITIONS OVER EUROPE DURING THE RELEASE

The meteorological situation during the 10 days of the release was fairly complex, with variable winds that carried the radioactivity from Chernobyl over almost all parts of Europe. At the time of the explosion on 26 April the skies were clear and the atmosphere over Chernobyl was dominated by an anticyclone centred over north-west Russia, resulting in low-level winds from the south-east (Figure 2). Below a height of about 500 m, however, the air had stabilized as a result of surface radiational cooling. Within this stable layer there was almost a calm with very little turbulent mixing taking place. Most of the initial debris, being very hot, easily penetrated this layer and rose to one or two kilometres where winds of about 10 m s^{-1} carried the debris towards the Baltic and Scandinavia.

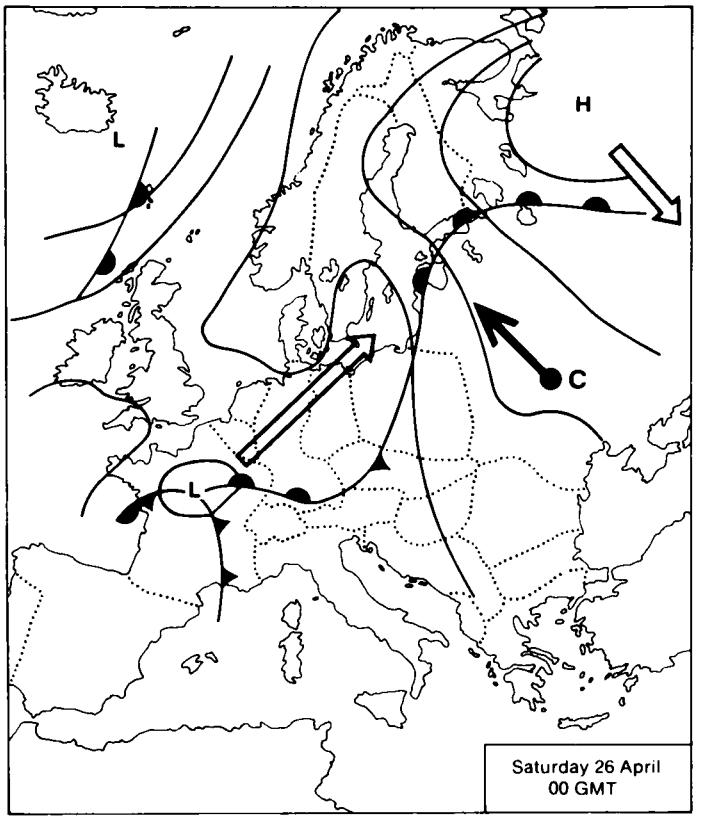


FIGURE 2. The synoptic situation nearly 4 hours after the initial explosion. Winds above the surface-based inversion carry the debris away from Chernobyl (C) towards the Baltic (closed arrow). A depression over France is moving north-eastwards and was to influence the later development of the plume. Open arrows denote subsequent movement of synoptic features.

The stable layer below 500 m in some ways protected the local population around Chernobyl from the immediate effects of the accident. Whilst the heaviest particles had sufficient fall-velocity to sink back to ground quite quickly, the smaller inhalable particles and the volatile gases were prevented from diffusing down to ground level where they could seriously impact upon the inhabitants. However, in partial balance to this, cooler emissions, emanating from the wrecked reactor after the initial explosion and from the burning debris spewed out on to the surrounding ground and buildings, would have been trapped by the stability, and would have given higher doses than otherwise to the people in the immediate locality.

Some time after sunrise, the stable layer must have broken down as the ground was warmed by the sun, and low-level winds would have increased. Subsequent emissions, being cooler, are believed to have been contained within the lowest 1500 m, with the mean height of the plume typically at around 500 m. The plume now followed the initial debris away towards the Baltic.

On Sunday, 27 April, the simple nearly-conical shape of the plume began to be distorted by vertical wind shear and by synoptic-scale variations in the horizontal wind field. Much of the initially ejected debris at greatest altitude was being drawn off to the east across central Finland and northern USSR. This 'finger' became detached from the rest of the plume and continued to move eastwards to be detected later in Japan and China (Figure 3).

By Monday, 28 April, an active depression that had been over France at the time of the explosion had moved into Sweden. Ahead of its cold front, a 'conveyor-belt' jet of warm unstable moist air dragged out a second finger from the plume, carrying radioactivity up over the warm front where much of the material was washed out in frontal rain. (A description of a similar jet appears later in the discussion of the debris over the United Kingdom.) Resulting depositions in central Sweden and parts of Norway were amongst the highest in Europe with Cs-137 levels in excess of 100 000 Bq m^{-2}, and were some three to

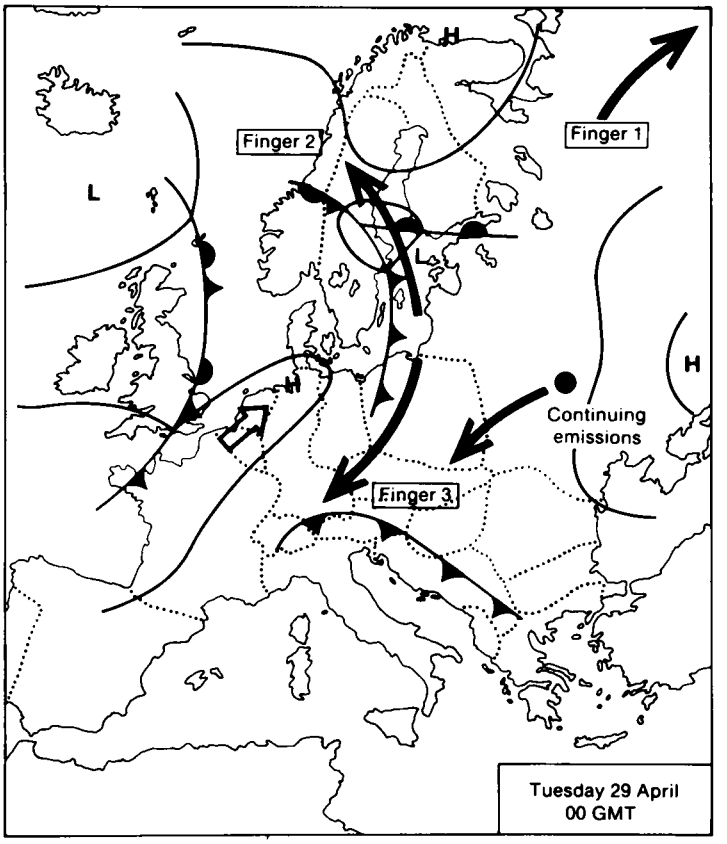


FIGURE 3. By Tuesday, 29 April, the plume had reached Scandinavia. The initially-ejected debris at greatest altitude was pulled off eastwards (Finger 1) over northern Siberia and was later detected in Japan and elsewhere. Some of the debris was caught in the 'conveyor belt' jet ahead of the cold front and was carried up over the core of the depression (Finger 2). Much activity was washed out in rain over central Sweden and Norway. The remaining debris moved south-westwards under the influence of a ridge of high pressure over the Low Countries (Finger 3). Some of it was later to cross the United Kingdom.

four times higher than the highest levels later deposited on the United Kingdom. The remainder of the activity in this finger travelled westwards out over the Norwegian sea, across Iceland and southern Greenland, and was later detected at very low concentrations along the eastern seaboard of North America.

After the passage of the depression, the pressure rose rapidly and a ridge of high pressure moved along a similar path to that of the depression, from the Bay of Biscay on Monday, 28 April, to reach southern Sweden by Friday, 2 May (Figure 4). This ridge caused a third finger to move south-westwards from the Baltic towards the Alps. Subsequent emissions from Chernobyl ran parallel and to the south of this finger crossing northern Italy and southern France late on Wednesday, 30 April. Meanwhile the finger had crossed Bavaria into central France. By Thursday, 1 May, as the high pressure area slipped away eastwards from the Low Countries, the plume over France turned northwards and by midnight had reached the English Channel, poised to cross into Britain in the early hours of Friday. A depression in the south-west approaches was beginning to deepen, and was to play a major role in what happened in the subsequent 3 days.

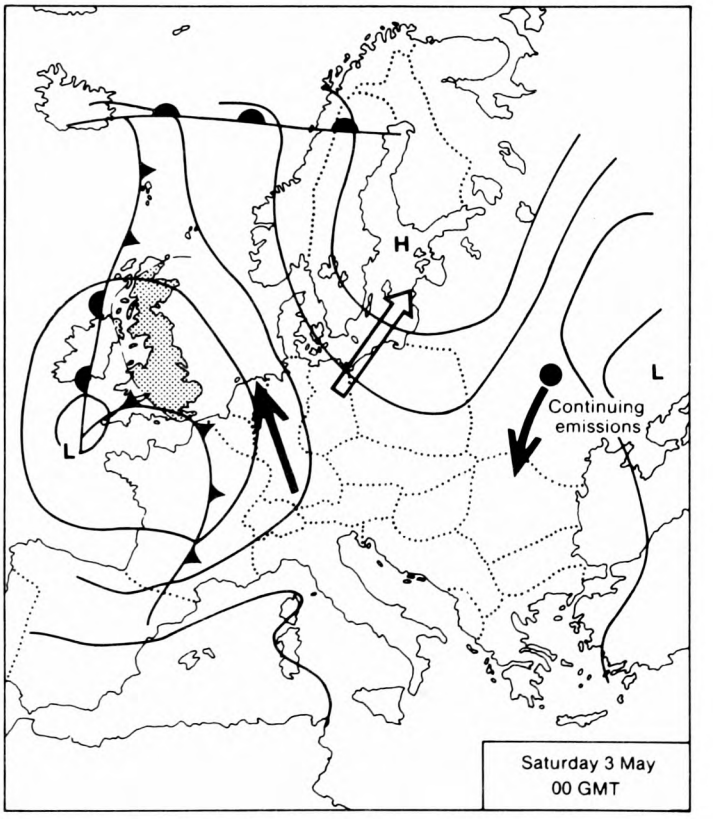


FIGURE 4. By Saturday, 3 May, debris from Finger 3 had crossed Bavaria and France and had moved into the United Kingdom and was being influenced by thunderstorms and the cold front associated with the deepening low off Cornwall. The stippled area shows the extent of the plume over the United Kingdom.

The sequence of plume positions and meteorological situations for each day starting on 26 April is illustrated in Figure 5. The plume positions are based partly on trajectory analyses and partly on an analysis of radiological measurements made at many sites across Europe. They are, however, only approximate. Figure 6 shows the probable track of that part of the plume which ultimately crossed the United Kingdom. Once over Scotland much of the remaining activity moved northwards but some was carried out westwards in the circulation of the depression and recrossed the United Kingdom later in the week at much lower concentrations. This part is shown in the Figure.

Before considering what happened over the United Kingdom, a reminder of loss processes is in order.

6. LOSS PROCESSES

Concentrations in the air near the ground, within the so-called mixing layer, gradually fell as a result of three processes. Firstly, the plume mixed with previously uncontaminated air through a process of turbulence. Secondly, some material must have escaped from the mixing layer, through clouds for example, to higher altitudes. Thirdly, and most importantly, because of deposition of radioactive material to the ground. Deposition is thought of as happening in two ways — dry deposition and wet deposition. Dry deposition is the direct uptake of material from the air as it comes into contact with the surface — sedimentation, absorption or impaction may be involved. It is a fairly continuous process as long as material is there to be deposited. Sedimentation, or gravitational settling, is particularly important in the immediate vicinity of the accident, but further afield wet deposition and other aspects of dry deposition predominate. Wet deposition, on the other hand, occurs much more sporadically, depending on the occurrence of rain or snow, or on 'occult' deposition — the scavenging of wind-blown contaminated cloud droplets by vegetation whenever cloud or fog is at ground level, as for example often occurs on the tops of hills.

Generally, dry deposition is more effective for reactive gases like I-131 than for particulates or aerosols like Cs-137. For the latter, size is very important whether dry or wet deposition is being considered. Unfortunately, little information is available concerning the size distribution in the Chernobyl plume

Wet deposition by rain-storms can halve the mass of airborne material in less than 30 minutes. Deep convective clouds which draw large volumes of contaminated air from the mixing layer through the cloud are particularly efficient in this respect. Large accumulated depositions of the material on the ground can result. In contrast, the highest concentrations in rain will often be associated with low rainfall rates or with occult deposition.

By far the largest depositions of radioactivity away from Chernobyl itself occurred in areas affected by rain. These included parts of Scandinavia and Eastern Europe, the Alpine areas, the United Kingdom and Ireland, and parts of Greece and Turkey.

7. RESULTS OF A SIMPLE, TWO-DIMENSIONAL MONTE CARLO TRANSPORT AND DISPERSION MODEL

At the time of the Chernobyl accident, there were several mathematical models available in Europe for simulating the movement and deposition of radio-nuclides from such a release.

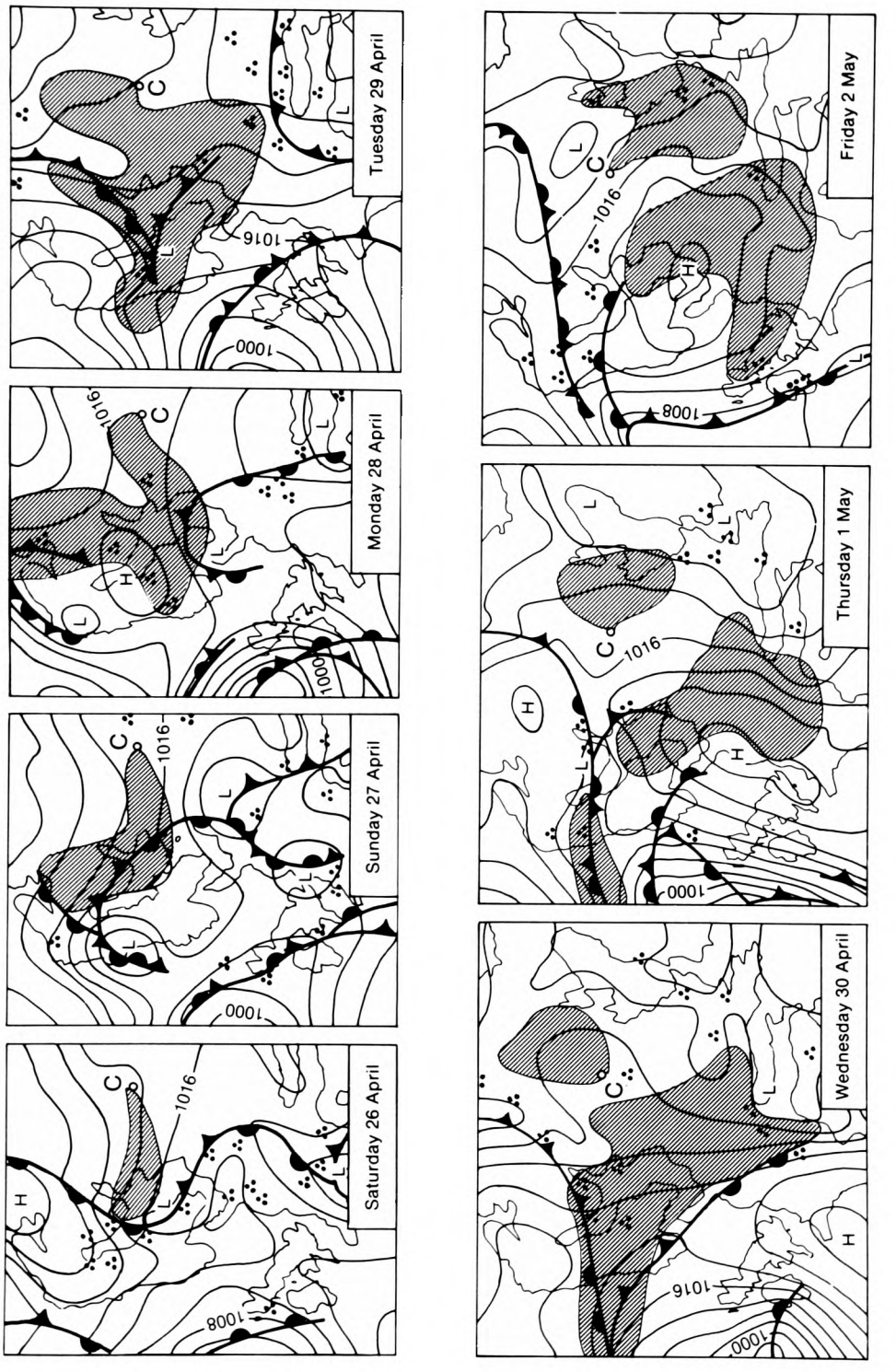


FIGURE 5. Daily synoptic maps with some indications of where rainfall (∴) was occurring. Superimposed are estimates of where the debris was at some time during each day. These shaded areas are inferred from trajectory analyses and from radiological measurements taken sometime during the day. Chernobyl is marked C.

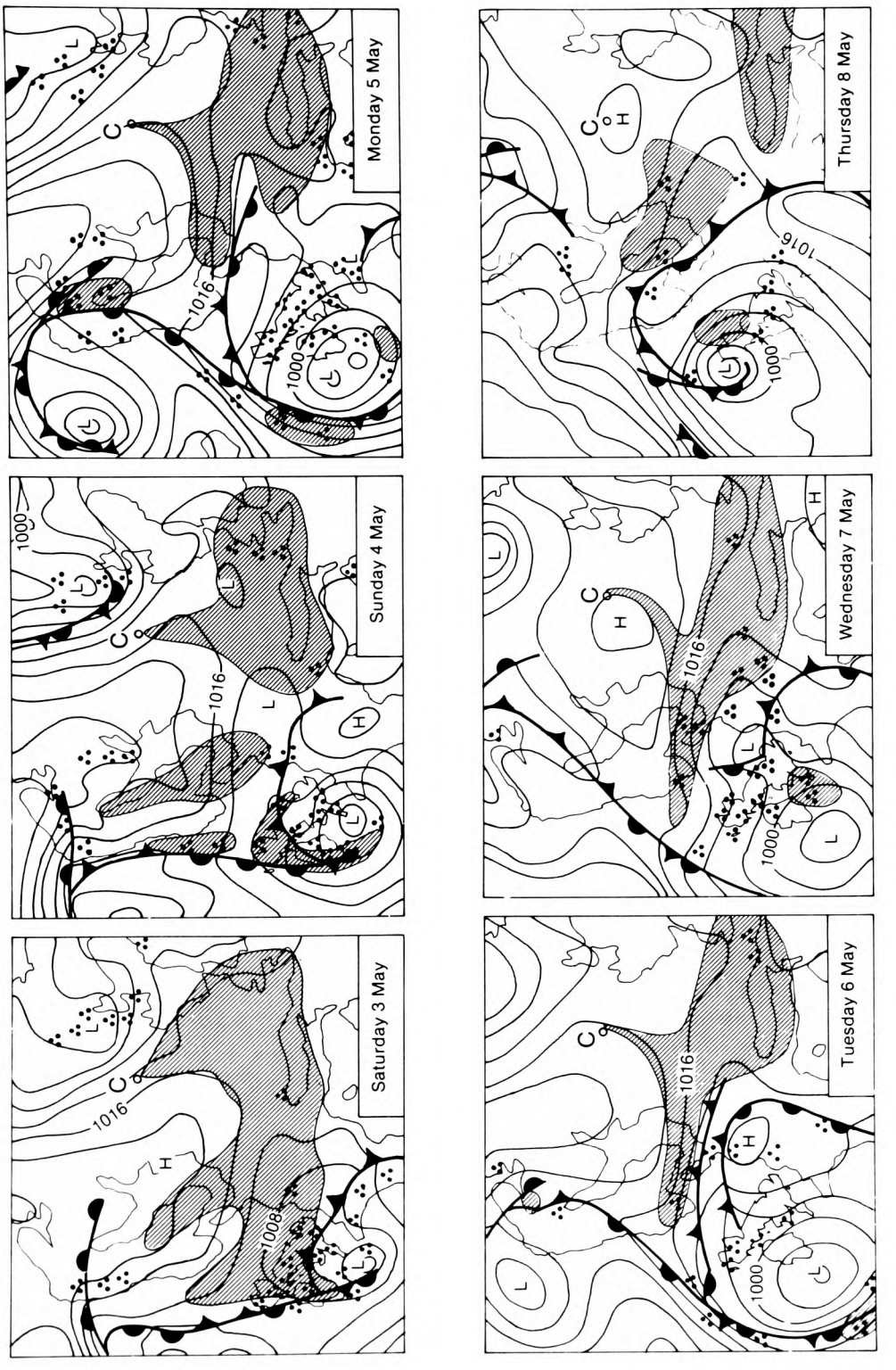


FIGURE 5 continued.

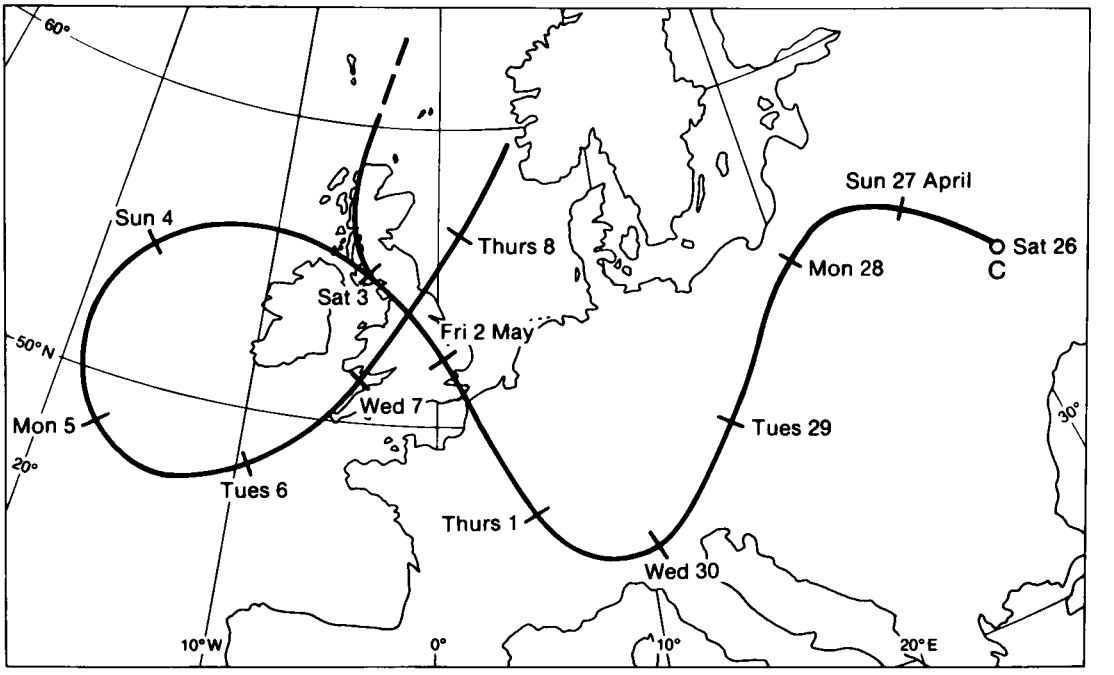


FIGURE 6. The track of the debris that ultimately crossed the United Kingdom showing its daily (1200 GMT) positions. On reaching Britain, fragments broke off and travelled round the depression to the south-west of the country and recrossed the United Kingdom later in the following week at much lower concentrations. The main body of the plume continued northwards, however, over the Norwegian Sea.

One of the best of these was the MESOS model developed at Imperial College, London. The results of this model when applied to Chernobyl have been described elsewhere (ApSimon *et al.* 1986). However, no model available in 1986 was ideally suited to predicting *in real time* and with sufficient accuracy the movement of the debris through the atmosphere and its deposition by wet and dry processes. Since that time many groups have been preoccupied with developing such operational models, including the Meteorological Office and NRPB, in conjunction with other UK centres of expertise, at the specific request of the UK Government. By the end of 1987 a basic two-dimensional model was completed, as a provision until a more complex fully 3-dimensional model can be developed. Its completion is expected soon after the end of 1989.

The basic model uses winds at a single specifiable level obtained from the output of the so-called 'fine-mesh model' whose grid-scale resolution is 75 km, or from the 'coarse-mesh model' (resolution 150 km). The two models belong to the suite of operational numerical weather prediction models in current use by the Meteorological Office. A succession of particles are released from the source, which move with the local interpolated wind, plus a random perturbation derived from a Gaussian distribution with zero mean and specified standard deviation σ. This random perturbation simulates the effect of sub-grid-scale motions and the influence of turbulent vertical motions through a field of wind velocity

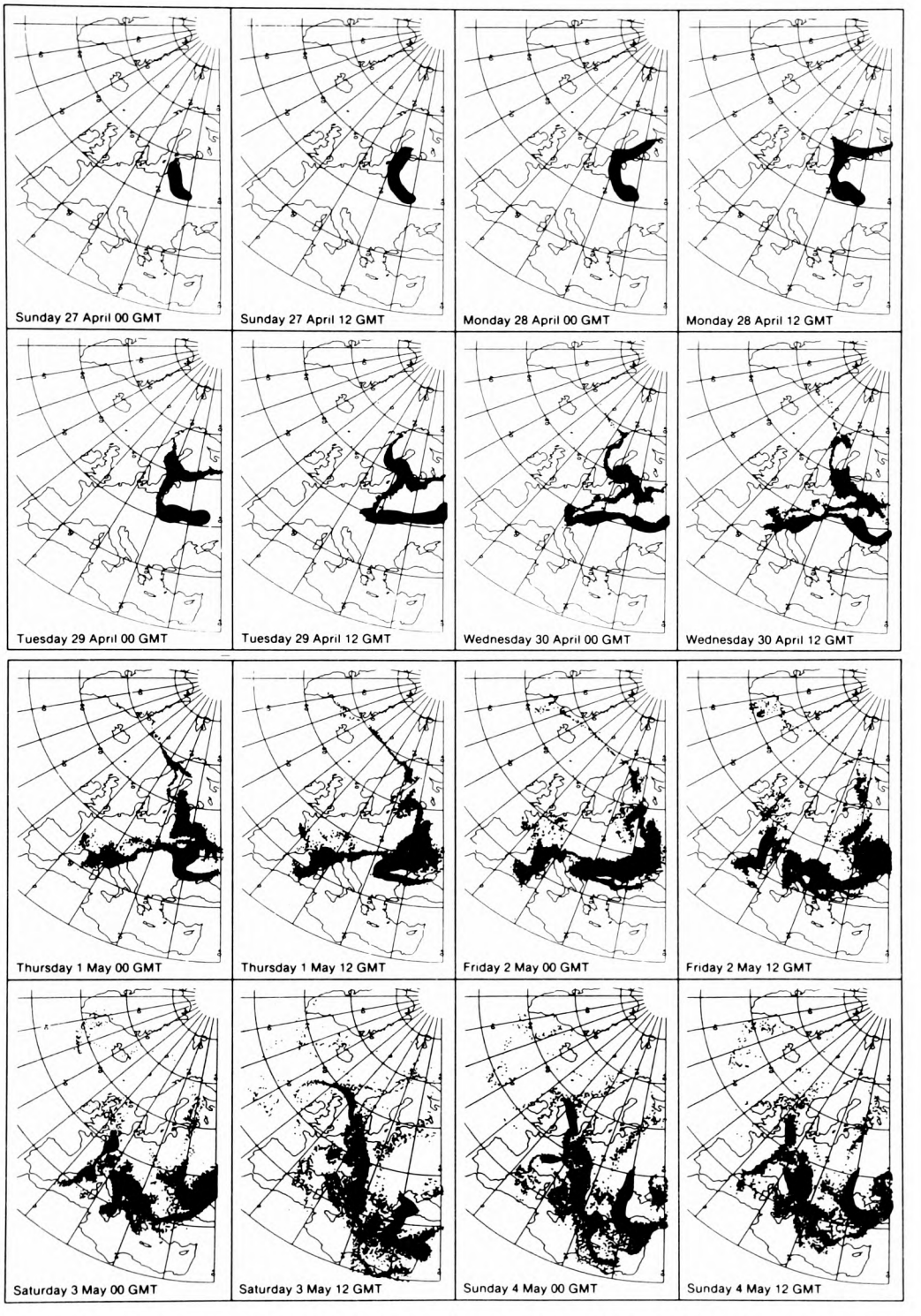


FIGURE 7. Simulation of the movement of debris from Chernobyl following the accident using a two-dimensional Monte Carlo model (see text). The results show the fibrous and rather convoluted nature of the plume under the action of synoptic-scale distortion.

which changes with height — a process which of course cannot be explicitly represented in a 1-level model. The perturbation is applied in both horizontal directions, has been given a standard deviation $\sigma = 1.5$ m s^{-1} and is held fixed within each hour for each particle. The activity associated with every particle is depleted in time to represent the combined effect of decay and dry deposition. Wet deposition is not included in the basic model. Fields of particles, of concentration in the air and of dry deposition, can be derived. The model can be used in a forecast mode as soon as an accident is notified, or in a hindcast mode (using just the diagnosed wind-field analyses) some time after the accident. Figure 7 shows the developing fields of particles at 12-hourly intervals using this basic model with winds derived at 850 mb* simulating the release of debris following the Chernobyl accident. In spite of the model's essential simplicity these fields generally fit the radiological observations surprisingly well, especially in regard to the time sequence of the plume's passage over the United Kingdom. The distortion of the plume by the synoptic wind field and the convoluted 'fibrous' character which emerges is of particular interest.

8. UK MEASUREMENTS OF THE AIRBORNE DEBRIS

8.1. *Radiological monitoring network*

At the time of the Chernobyl accident the majority of monitoring stations were positioned at nuclear installations. Generally they were designed to alert local management to accidental release of radioactivity from sources held on the premises. Numbers were small, being but 27 in all, with some grouped in rather small geographical areas. Instruments varied from site to site; some held γ-ray detectors, others measured gross-β concentrations, whereas others took air samples which could be subsequently analysed for a range of nuclide concentrations. Because of their intended locally orientated use, no co-ordinated systematic monitoring programme was in operation, and the duration over which individual samples were averaged or collected varied quite widely. Although these differences caused some difficulties in the derivation of the plume's movement across the United Kingdom, without them the task would have been impossible.

8.2. *Measurements from the monitoring stations*

Figures 8 and 9 show samples of the measurements made. Figure 8 shows records from γ-ray detectors, one at Berkeley Nuclear Laboratories in Gloucestershire, the other from the Central Electricity Generating Board (CEGB) nuclear power station at Trawsfynydd in Gwynedd (North Wales). The records show the Chernobyl activity causing prolonged peaks rising only some 10–20% above the rather high 'noisy' background trace. The instruments are largely shielded from γ-rays emanating from deposited activity on the ground below the instrument, but the slowly declining levels evident in the Trawsfynydd trace, even though the main airborne plume had long since passed by, suggests deposited material must have been influencing the observations indirectly, perhaps by wind-blown resuspension.

* 850 mb is a surface of constant pressure, corresponding very approximately to a height of about 1500 m above ground.

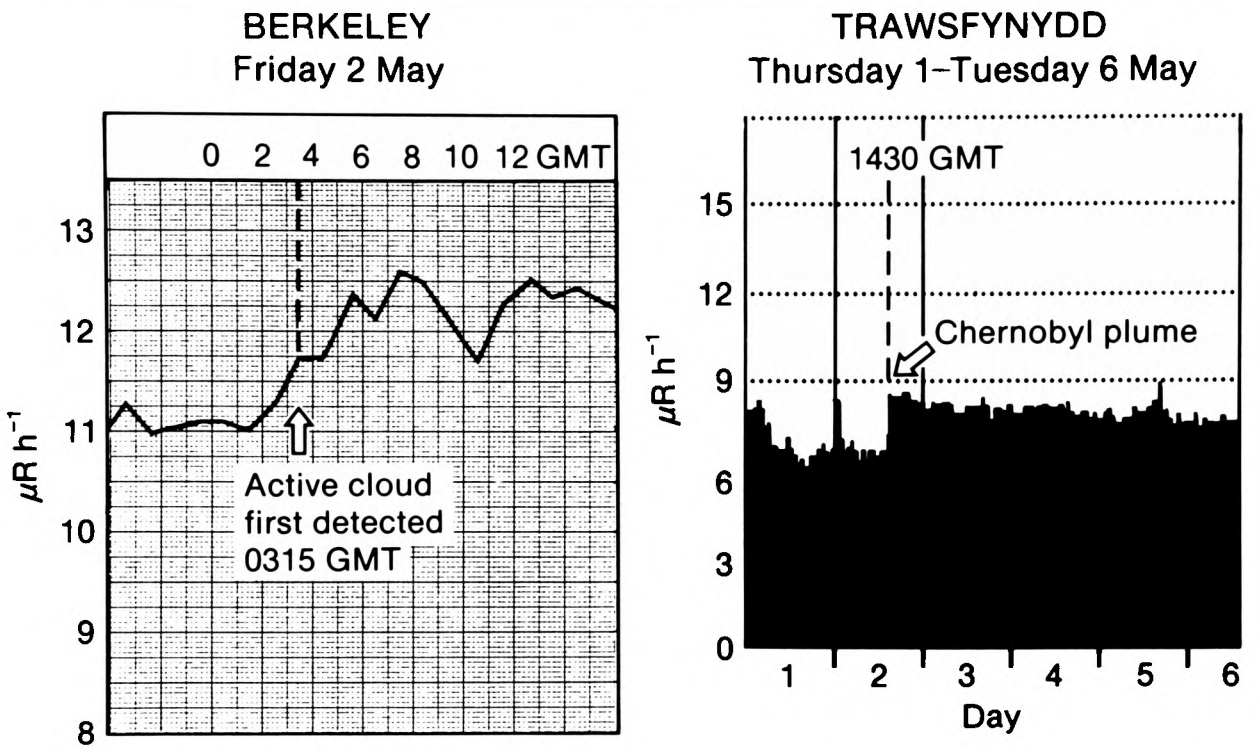


FIGURE 8. γ-ray records during the early part of May 1986 showing the increase in activity above background as the Chernobyl plume arrived. The records are from the Berkeley Nuclear Laboratories in Gloucestershire and Trawsfynydd in Gwynedd, North Wales. (Private communication, I.M.G. Thompson, CEGB, 1987)

Figure 9 shows measurements of I-131 and gross-β at 13 stations where fairly continuous monitoring took place from Friday, 2 May to Sunday, 4 May during the passage of the plume. There are at least two points to notice. Firstly, several stations commenced detailed monitoring too late to catch the arrival of the plume. Secondly, data points at some stations are believed to be plotted at the time corresponding to the end of the sampling interval (which in many cases is several hours long) and therefore the apparent arrival time of the plume is later than the real arrival time. This is particularly apparent at Berkeley where comparison with the continuous γ-record suggests a significant delay of several hours. Some workers have, however, suggested that there may have been a real separation in time between the strongest γ-emitters and the nuclides contributing to the records in Figure 9, due to a differential release pattern at Chernobyl itself — this question has not been finally resolved. However, if the separation hypothesis is a contributory cause it is doubtful if it is the whole cause of the mismatch in the timings since some other stations exhibited a very much smaller difference.

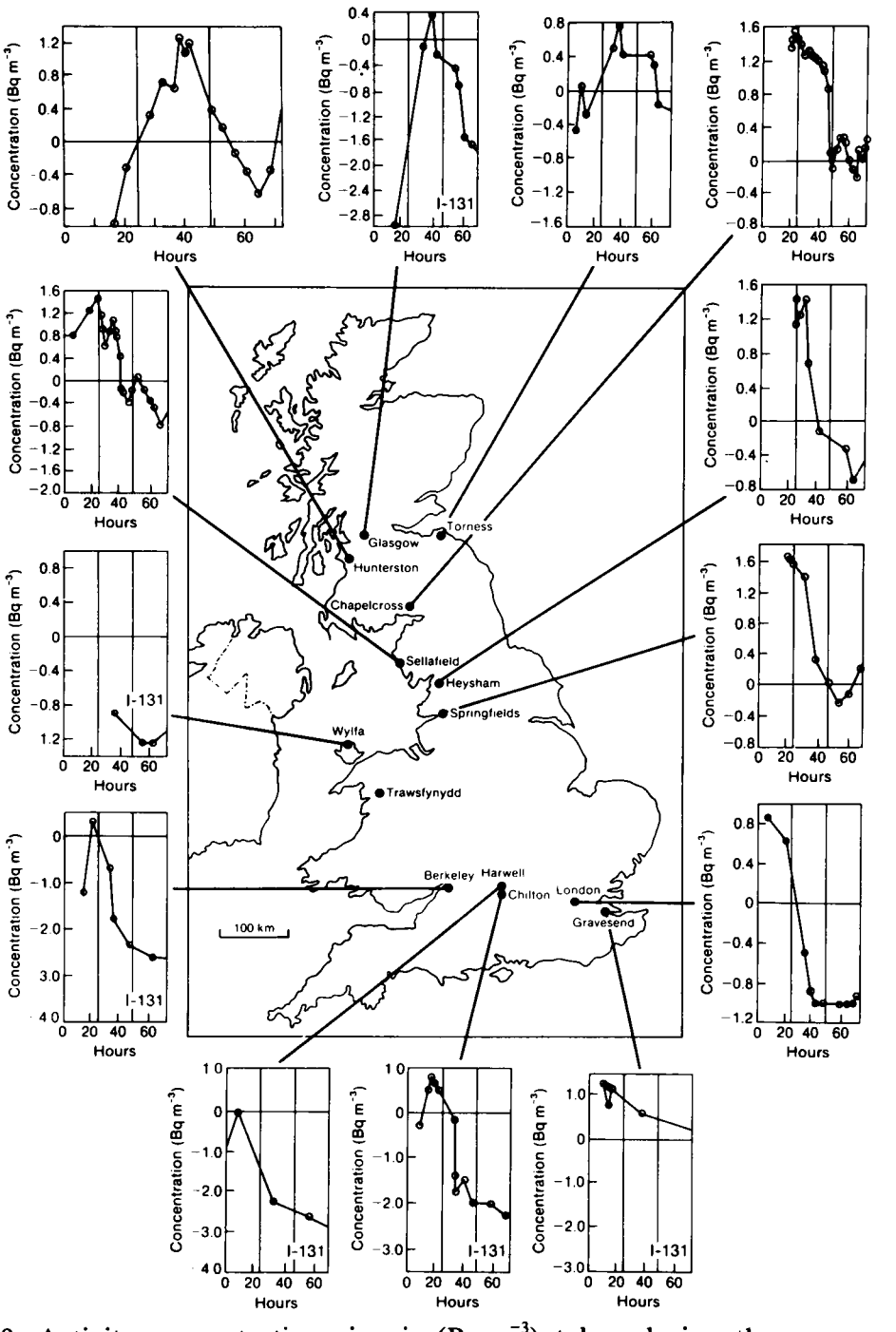


FIGURE 9. Activity concentrations in air (Bq m^{-3}) taken during the passage of the Chernobyl plume. Records of I-131 are so marked; the remainder refer to gross-β. The logarithm of concentration is plotted on the ordinate and time in hours (beginning 0000 GMT Friday) on the abscissa. Vertical lines separate Friday, Saturday and Sunday (2, 3 and 4 May).

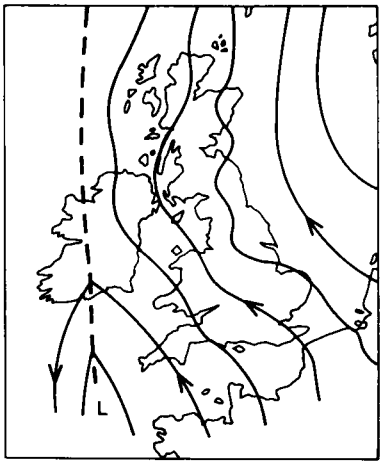


FIGURE 10. The surface synoptic pattern for time shown on Friday, 2 May 1986.

9. THE PROGRESSION OF THE PLUME OVER THE UNITED KINGDOM

9.1. *Friday, 2 May 1986*

Friday was a beautiful warm sunny day over the southern half of Britain with temperatures reaching 22 °C in Berkshire. Winds were from the south drawing in continental and mediterranean air over the country. A depression to the south-west of Cornwall was deepening however and moving into the approaches to the Bristol Channel. Some instability and showers were experienced over North Wales, Cumbria and western Scotland in the latter part of the day with accumulated rainfall up to 0900 GMT on Saturday morning reaching over 5 mm at a few isolated places in Wales and Cumbria, and up to 12 mm at Wigtown in south-west Scotland.

9.1.1. *0000–0600 GMT.* The Chernobyl plume had reached the north coast of France by midnight. The southerly winds carried the leading edge of the plume to the Channel coast of England by 0300 GMT and over much of southern England (excluding the south-west) by 0600 GMT (Figure 10). The western edge of the plume seems to have remained rather static for most of Friday, extending from about Lyme Bay on the south coast to Bridgwater in Somerset. The arrival time at Berkeley according to Figure 11 is in reasonable accord with the γ-ray timing of Figure 8.

9.1.2. *0600–1200 GMT.* At 0900 GMT, the geostrophic wind was about 10 m s^{-1} from the south-east and was fairly uniform over England and Wales. In 3 hours this is equivalent to a movement of the leading edge of the plume of just over 100 km as seen in Figures 11, 12 and 13. By 1200 GMT the winds had eased over Wales as a small heat low (L_0) developed, but had strengthened over north-east England accelerating the movement of the plume over the Pennines towards Cumbria. The first shower of rain was reported near Montgomery in mid-east Wales at 1200 GMT.

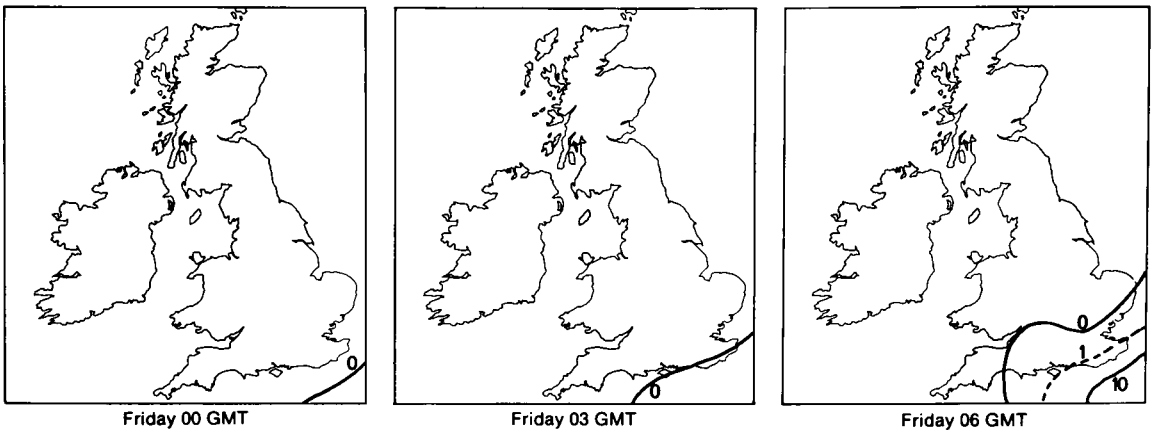


FIGURE 11. The movement of the Chernobyl plume into the United Kingdom at the times shown on Friday, 2 May. The plume is defined here by three contour lines of β-activity in air above background levels: 10 Bq m^{-3}, 1 Bq m^{-3} and zero.

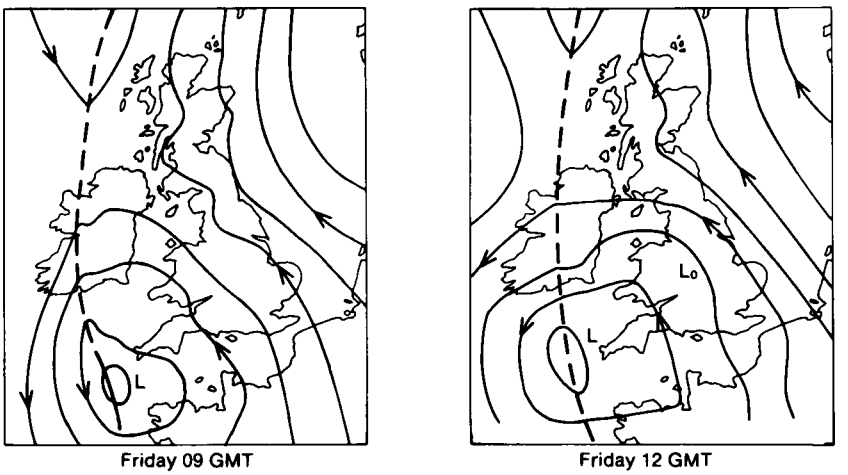


FIGURE 12. As Figure 10 but for times shown 2 May.

9.1.3. *1200–1800 GMT.* The shallow heat low intensified and stagnated over the Lancashire and North Wales area during this period leading to very light low-level winds there and very slow progression of the plume. The low spawned a series of moderate showers over the northern mountains of Wales leading to some wet deposition of activity between 1300 GMT and 1500 GMT (Figures 14 and 15). Amounts of rain are difficult to ascertain since further rain fell on Saturday morning before the rain-gauges were monitored. Weather radar pictures of the two periods suggest about one third of the day's total may have fallen

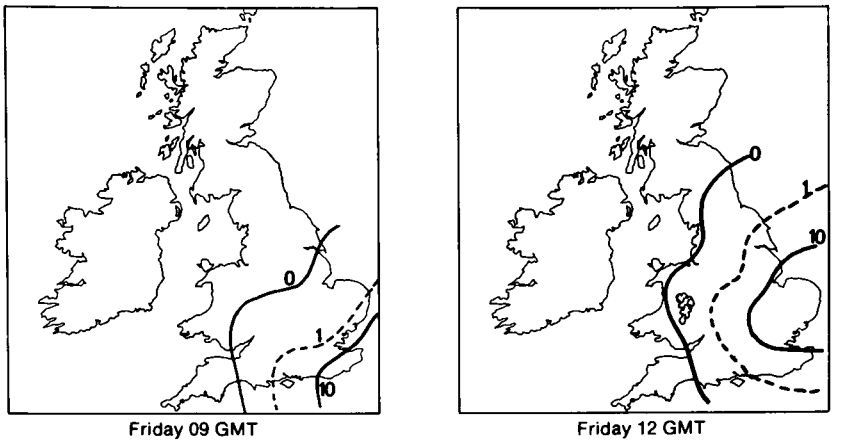


FIGURE 13. Plume positions as Figure 11 but for times shown 2 May. In this and later figures, areas within which rain was reported are delineated, although rain may not have affected the total area.

during Friday afternoon over Snowdonia (i.e. about 1–2 mm). The heat low intensified the pressure gradient to the north over the most northern parts of England, pushing the plume rapidly into southern Scotland. Whilst the remainder of England was still enjoying unseasonable warm sunny weather, the Cumbrian coast experienced some heavy showers between 1600 and 1800 GMT, and the showers that had affected North Wales earlier moved northwards and became heavier, crossing the Isle of Man at about 1700 GMT and Dumfries and Galloway at 1800 GMT. The first report of a thunderstorm was at Dumfries itself between 1700 and 1800 GMT.

9.1.4. *1800–2400 GMT.* The heat low (L_0) over Lancashire drifted gradually northwards ending up over Dumfries and Galloway. A second heat low (L_1), initially over northern France, moved slowly over the Strait of Dover by midnight. The brisk winds to the north of the first heat low turned to the north-east, advecting a 'nose' of the plume south-westwards across Ulster into the Irish Republic (Figures 16 and 17). A second smaller 'nose' probably broke off from the plume over Wales, as a result of the fresher easterly winds over the Irish Sea, and crossed along the south coast of Ireland where moderate rain probably resulted in significant wet deposition of activity.

Occasional showers over south-west Scotland continued off and on until midnight. Meanwhile some ominous reports of thunderstorms over the English Channel boded ill for the day to come.

9.2. *Saturday, 3 May 1986*

The plume initially centred over northern England drifted slowly northwards to end up centred over the Scottish Highlands. Fresher north-east winds off the western side of Scotland vented some of the plume away across Ireland. The fine weather over much of England on Friday broke down completely as thunderstorms advected in from France and a cold front associated with the active depression off south-west England swept a band of rain

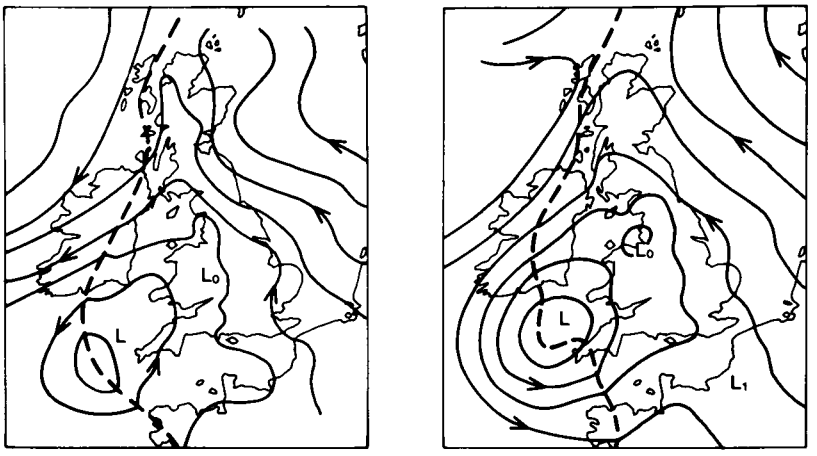


FIGURE 14. As Figure 10 but for times shown 2 May.

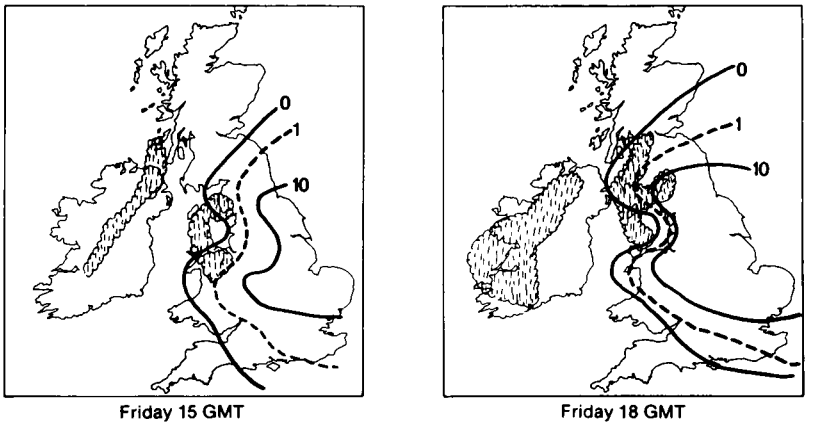


FIGURE 15. As Figures 11 and 13 but for times shown 2 May.

across south-west England and Wales. Heavy rain linked to both these causes led to very significant wet deposition over much of the British Isles and a marked reduction in the airborne load of activity.

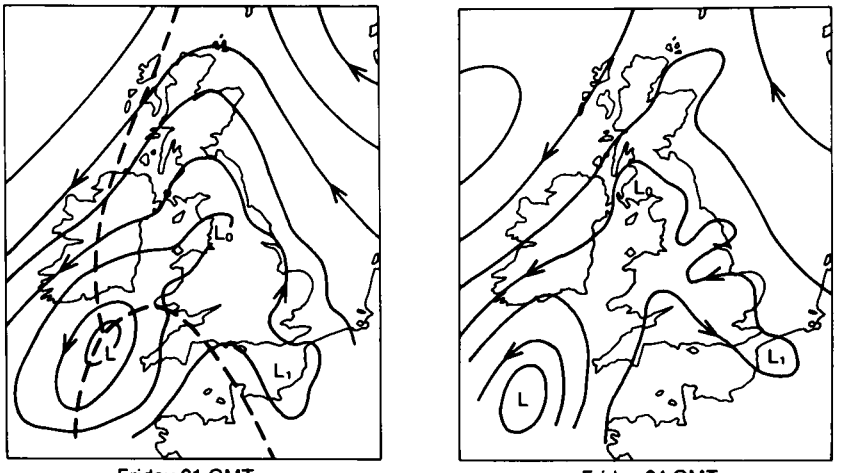


FIGURE 16. As Figure 10 but for times shown 2 May.

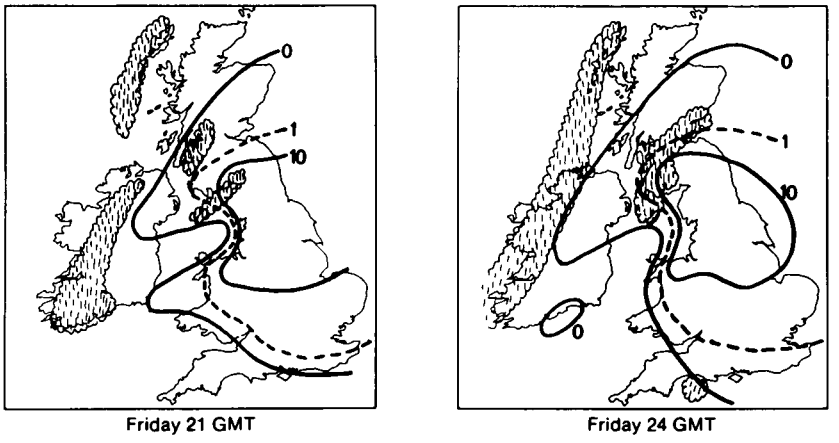


FIGURE 17. As Figures 11 and 13 but for times shown 2 May.

9.2.1. *0000–0600 GMT.* Winds were light and very variable over the United Kingdom and in consequence the plume moved very little during this period (Figures 18 and 19). The first heat low, L_0, was almost stagnant but the second low, L_1, drifted slowly northwards into

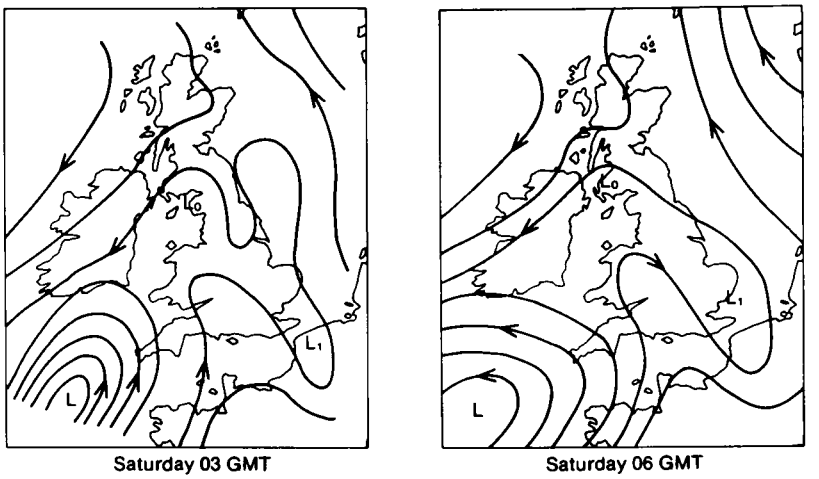


FIGURE 18. As Figure 10 but for times shown 3 May.

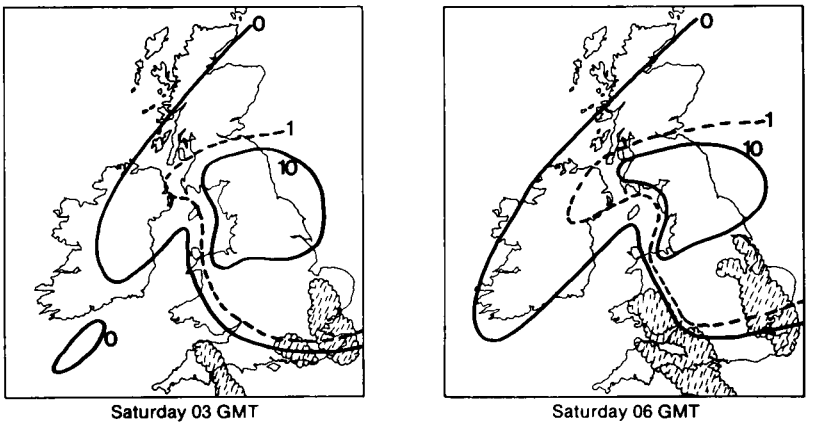


FIGURE 19. As Figures 11 and 13 but for times shown 3 May.

East Anglia. Active thunderstorms were embedded in L_1 as shown in the radar picture at 0100 GMT (see Figure 20). These storms moved rapidly northwards into the rear of the plume during this period, the leading storm reaching Humberside by 0600 GMT. It is

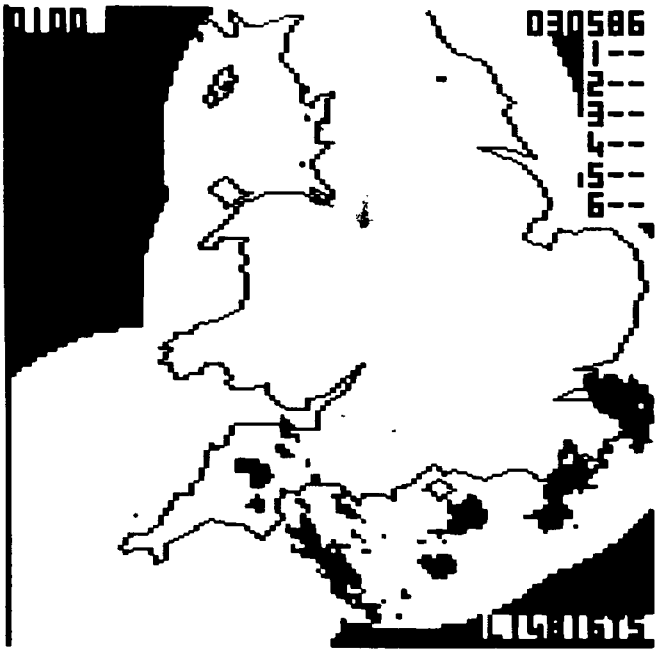


FIGURE 20. Weather radar picture for 0100 GMT on Saturday, 3 May, showing thunderstorms moving northwards from France into southern and south-eastern England.

interesting to note that London appears to have reinvigorated a storm passing overhead, owing perhaps to its enhanced surface roughness and temperature. Anyway, a footprint of rainfall was left to the north of the city.

The first consequences of the cold front were also evident at 0100 GMT over Devon and in the English Channel. From 0430 GMT onwards, it became clear that the rain linked to the front was in two bands about 100 km apart (see Figure 21). Details of the frontal structure are given later.

9.2.2. *0600–1200 GMT.* Apart from the progression of the 'nose' over Ireland, the plume continued to move very little because of the light winds at low levels engendered by L_1 which drifted gradually from East Anglia to north-west England (Figures 22 and 23). The thunderstorms over eastern England abated for a while with little to maintain them at full strength. The double-structured rain belt in the south-west moved gradually into mid Wales and the western Midlands. Moderate rain over the Black Mountains north of Abergavenny between 0900 and 1000 GMT may have been responsible for the localized significant deposition of Cs-137 (nearly 6000 Bq m^{-2}) in the area revealed by Atomic Energy Research Establishment (AERE) measurements on behalf of the Welsh Office (Cawse *et al.* 1988). Further to the north-west, at around 0900 GMT, heavy rain gave significant wet deposition in the hills between Aberystwyth and Rhayader. Estimating fairly precise values of deposition in this area is extremely difficult, taking into consideration the complex interaction of the front with the tail-end of the plume. Later maps will show our best estimates in mid Wales.

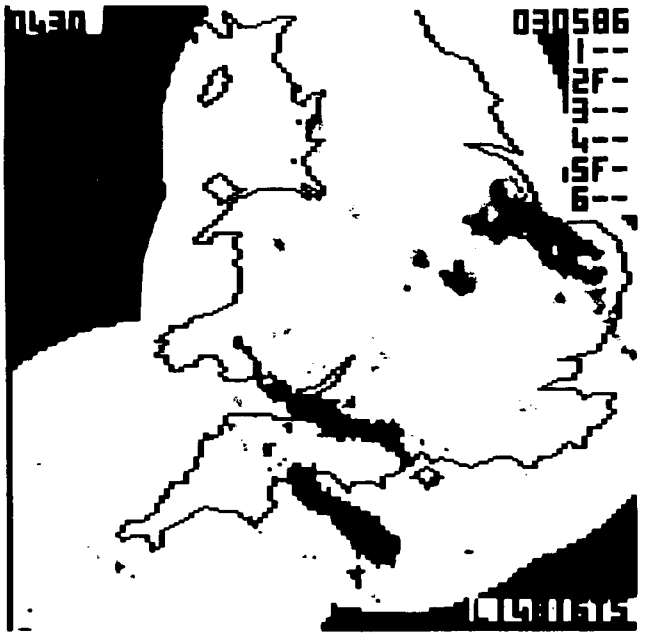


FIGURE 21. Weather radar picture for 0430 GMT on Saturday, 3 May, showing thunderstorms over The Wash and Lincolnshire and two bands of rain over south-west England associated with a cold front.

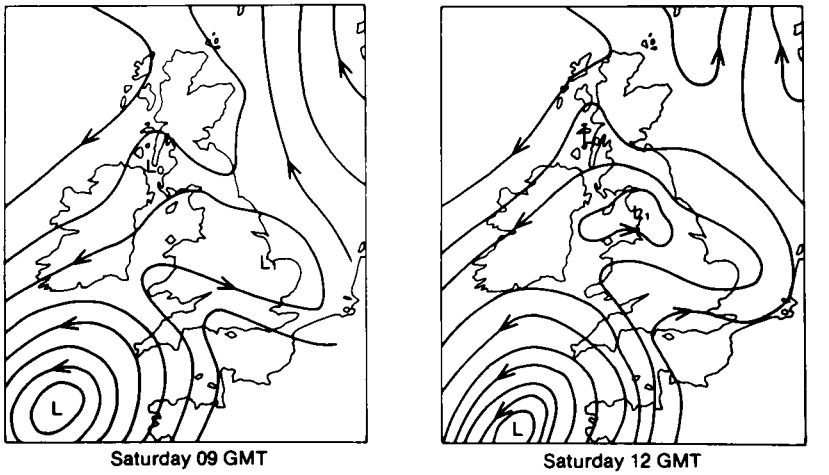


FIGURE 22. As Figure 10 but for times shown 3 May.

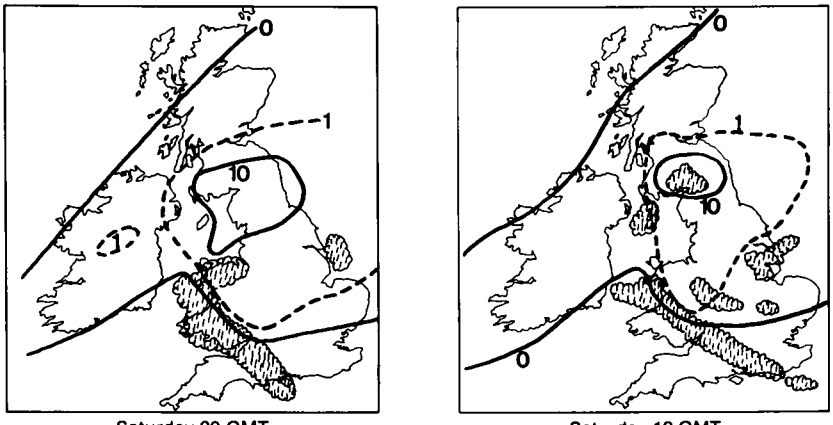


FIGURE 23. As Figures 11 and 13 but for times shown 3 May.

9.2.3. *1200–2400 GMT.* L_1 continued to move north-westwards only very slowly. The instability associated with the first band of frontal rain had moved sufficiently far north to reinforce the instabilities associated with L_1 and the thunderstorms moving up from the eastern Midlands (Figures 24 and 25). This enhancement, plus the effect of the Pennine hills and the Irish Sea, set the cumulonimbi off again and very vigorous storms developed over Cumbria, the Isle of Man, Ulster and south-west Scotland. Unfortunately the weather radar at Hameldon Hill in north-west England chose this key time to be somewhat unreliable and several pictures in the sequence are missing. However, it is clear from what is available (see, for example, Figure 26) and from the rainfall patterns obtained later from the fairly dense network of surface rain-gauges that the storms travelled north-westwards across the area leaving narrow bands of rainfall and associated deposited activity. One of the most vigorous storms (maybe the same storm influenced by London referred to earlier) re-emerged over the Skipton area of Yorkshire, crossed Cumbria just north of Keswick, was strengthened by crossing the Solway Firth, passed over the Southern Uplands near Benbrack, and then moved out over the Firth of Clyde affecting north-east Arran and beyond. A similar storm started near Birmingham, passed over Clwyd, was strengthened by the Irish Sea and gave heavy rain over the mountains of Antrim in Ulster in the second part of this period, around 2100 GMT. The area of the plume significantly contracted during this period as the storms drew into their systems the low-level contaminated air, rather like giant vacuum cleaners drawing in the dust, and washed out much of the activity to be deposited on the underlying surface.

9.3. *Sunday, 4 May 1986*

On Sunday the centre of the depression that had been very slow moving to the south-west of Cornwall began to move north-westwards over Ireland and to fill. Heat low L_1 moved across

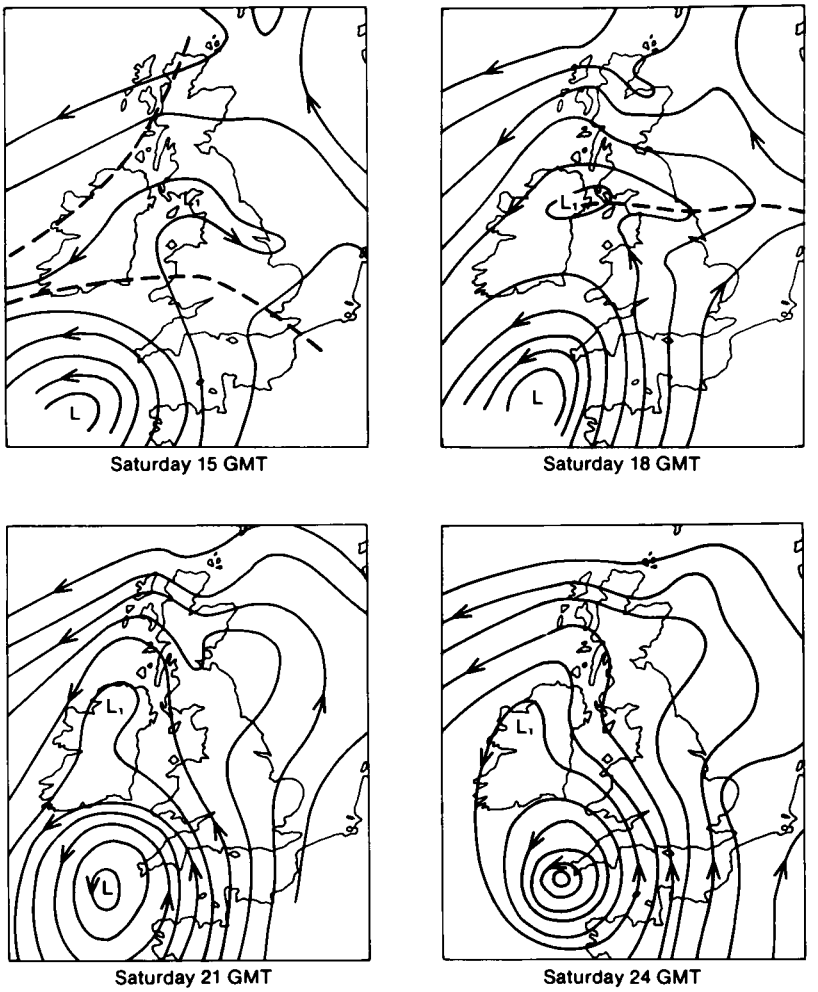


FIGURE 24. As Figure 10 but for times shown, 3 May.

Ulster and out into the Atlantic whilst another heat low, originally linked with L_1, moved northwards up the east coast of Scotland giving slack winds over much of Scotland during the early hours (Figures 27 and 28). By midday brisk south-easterly winds had become established right across Scotland. Showery rain was largely restricted to the coastal areas. Even though air concentrations of radioactivity had fallen dramatically as a result of Saturday's thunderstorms, they were still high enough in some parts of the plume to give one of the highest recorded concentrations in rain at Dounreay on the northern Scottish coast. Concentrations in rain tends to be related quite strongly to the intensity of the rain — light rain is often associated with high concentrations since the radioactive particles may provide the nuclei on which raindrops can form, and the smaller the raindrops are when they reach the ground, the higher is the proportion of the nucleus to the total mass of the drop.

The main body of the plume, centred over the Highlands, moved slowly at first. A section is believed to have broken off from the plume and moved westwards with heat low L_1 around

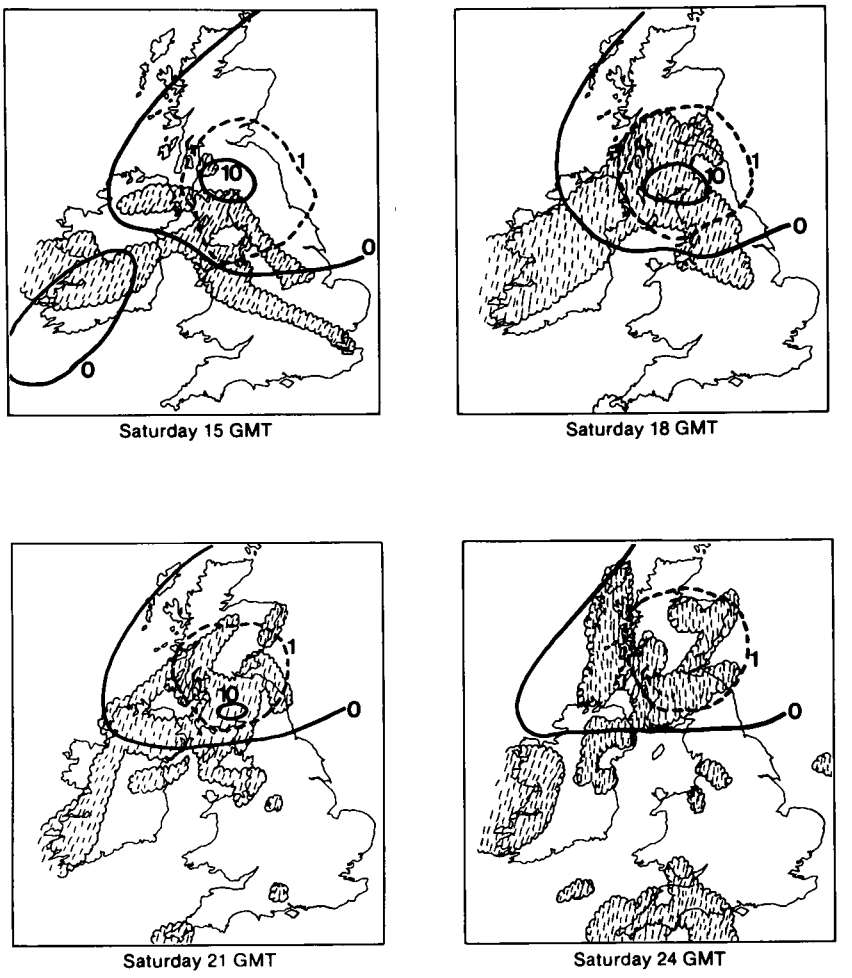


FIGURE 25. As Figures 11 and 13 but for times shown, 3 May.

the circulation of the depression. Later, the main body of the plume drifted gradually northwards until by midnight it was virtually clear of the United Kingdom, except for remnants of the breakaway sections of the plume which under the influence of the depression recrossed the country in the following few days with concentrations one or two orders of magnitude smaller than had been experienced over the weekend.

10. THE EFFECT OF THE COLD FRONT

The movement of the plume over the British Isles has been discussed. The deepening depression to the south-west of the United Kingdom not only helped to advect the plume northwards and westwards but also helped to revitalize the instability of the air mass carrying the Chernobyl debris. This led to widespread rain in many areas. On 3 May the

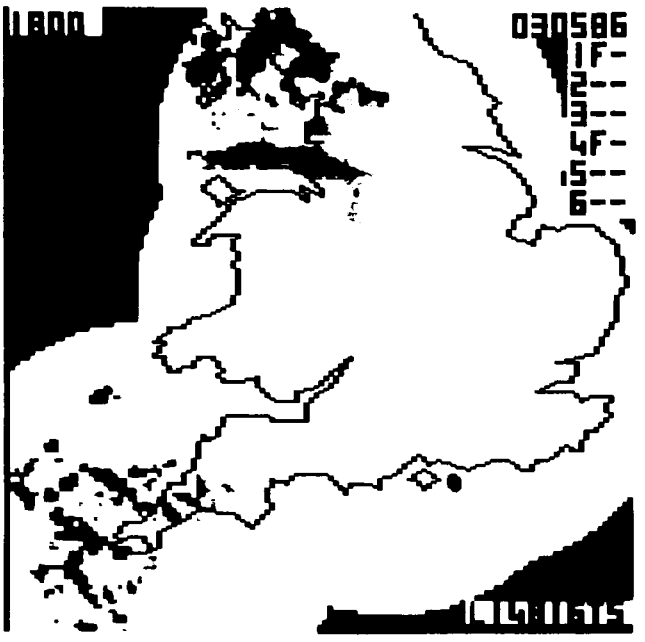


FIGURE 26. Weather radar picture for 1800 GMT on Saturday, 3 May, showing thunderstorm activity over Lancashire, Cumbria and the Isle of Man.

southerly extent of the plume was limited by a cold front, associated with the depression, which was moving northwards across the country.

An analysis of this front by Monk and Jonas (1987) shows it to be a rearward-sloping cold front (see Figure 29). Such fronts are characterized by the warm air in the so-called 'warm conveyor belt', with high wet-bulb potential temperature, rising relative to the advancing frontal system over dry descending air. The cloud and rain lie on and to the rear of the surface cold front. At the front itself the air may ascend rapidly through a 2–3 km deep layer, giving a rather narrow line of heavy precipitation (Figure 30). Behind the front, where the ascent is slower, the precipitation is lighter (Browning *et al.* 1987).

On 3 May the effect of this sort of cold front was evident in Gloucestershire and parts of southern and central Wales. Measurements of the depositions on grass found by the Institute of Terrestrial Ecology in these areas are displayed in Figure 31 and show the result of this rainfall. It appears that the southern edge of the plume was probably advected up this rearward sloping surface and some of the radioactivity was washed out in the accompanying rain. Consequently activity was found in the rain originating aloft at the same time when nuclide concentrations in the air at the ground (in the 'cold' air behind the front) were effectively zero.

This of course renders the simple equations for total deposition, derived and discussed later in this Report, rather useless in these circumstances. Nevertheless, Figure 39 shows the estimates of Cs-137 wet deposition in these areas, derived by assuming plausible (but unverified) concentrations of caesium in the air aloft ahead of the front.

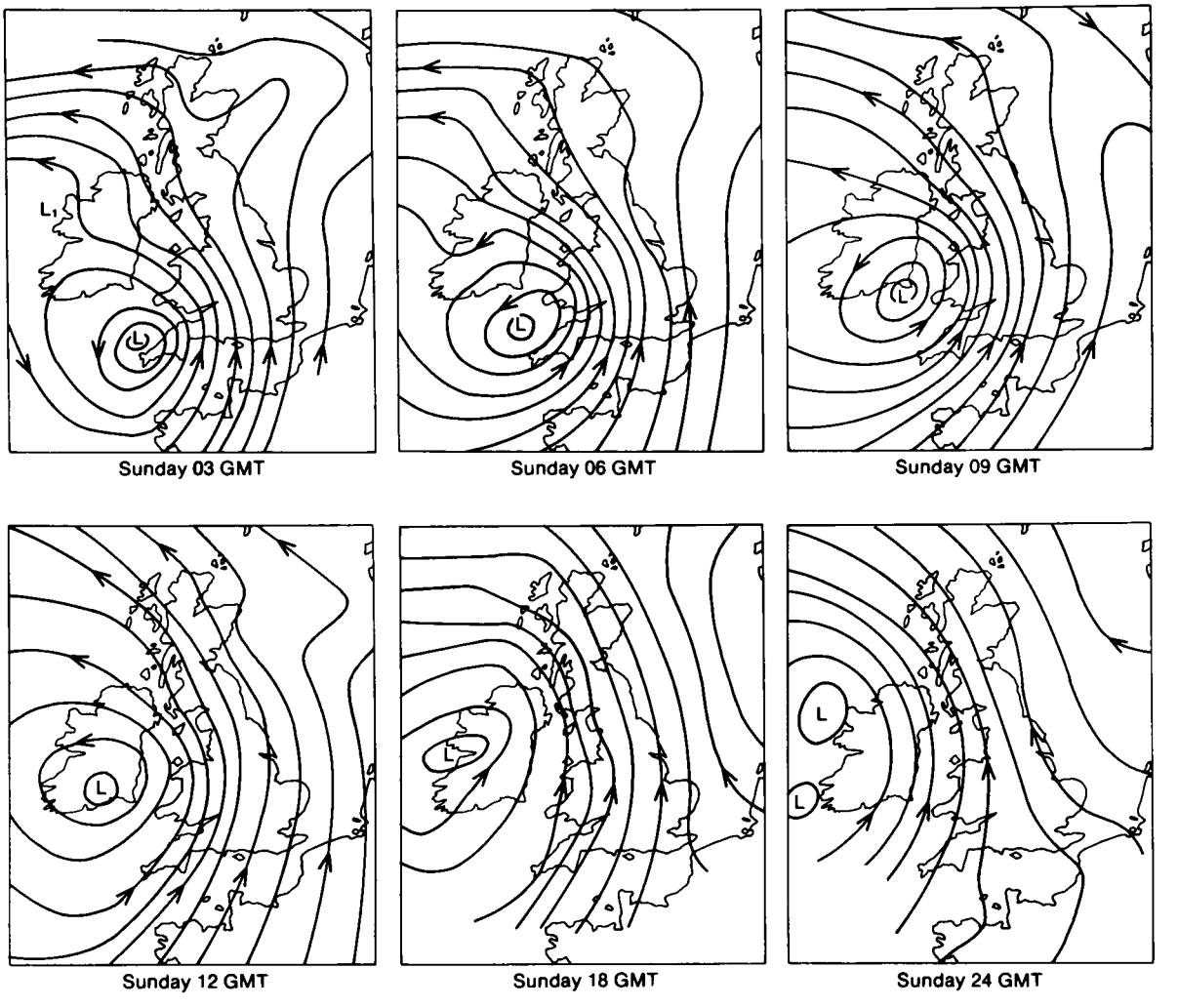


FIGURE 27. As Figure 10 but for times shown, 4 May.

11. RAINFALL INTERCEPTING THE PLUME

As discussed earlier, precipitation is an efficient process for removing radioactive debris from the air in which the precipitation forms or falls through. Consequently, to make a proper assessment of deposition, the only alternative to a direct survey of levels of activity in soils and vegetation is to assess the spatial and temporal profiles of activity in the air and details of the rainfall. Although a fairly large number of meteorological observing stations record rainfall and report these observations in a matter of an hour to the Meteorological Office Headquarters in Bracknell, the density of these stations is insufficient to assess, in any kind of detail, the rainfall (and hence the deposition) field. However a much greater network of over 4000 rain-gauge stations exists but these are run by other organizations (for example the water boards) or by volunteer members of the public with other more climatological

FIGURE 28. As Figures 11 and 13 but for times shown, 4 May.

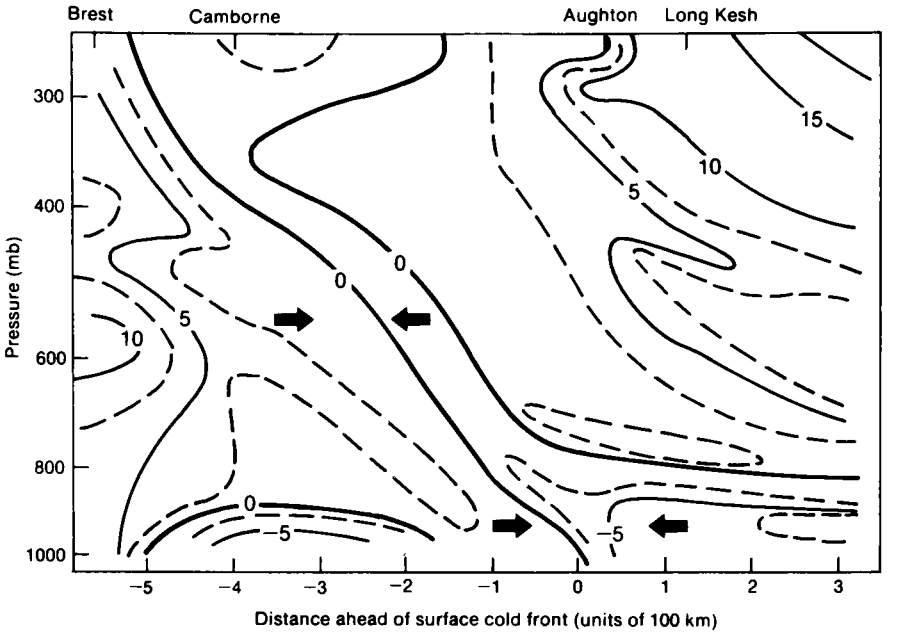


FIGURE 29. Vertical cross-section normal to the surface cold front at 1200 GMT on 3 May showing velocity components ($m\,s^{-1}$) normal and relative to the surface front. Positive velocities are in the direction of frontal movement. The speed of the front (left to right) is assumed to be $5\ m\,s^{-1}$. The rearward slope is seen in the slope of the zero relative velocity contour between the pairs of arrows.

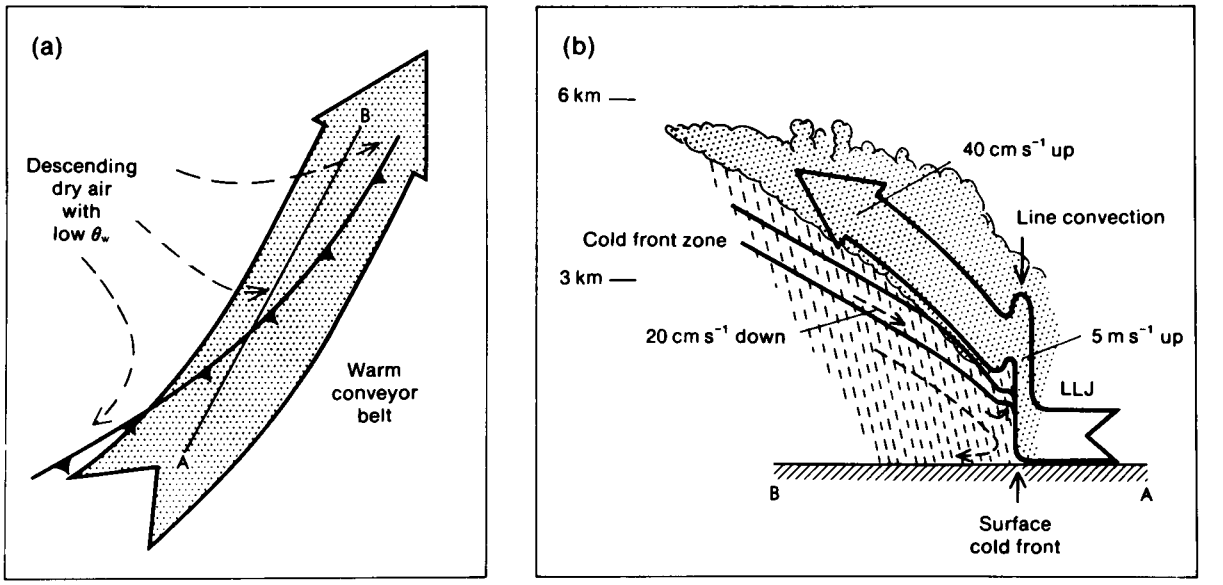


FIGURE 30. Schematic portrayal of the airflow in a classical cold anafront showing the warm conveyor belt (stippled arrow) undergoing rearward-sloping ascent above the cold-frontal zone. (a) Plan view. (b) Vertical section along AB in (a); flows are shown relative to the moving frontal system and LLJ marks the axis of a low-level jet (from Browning 1985).

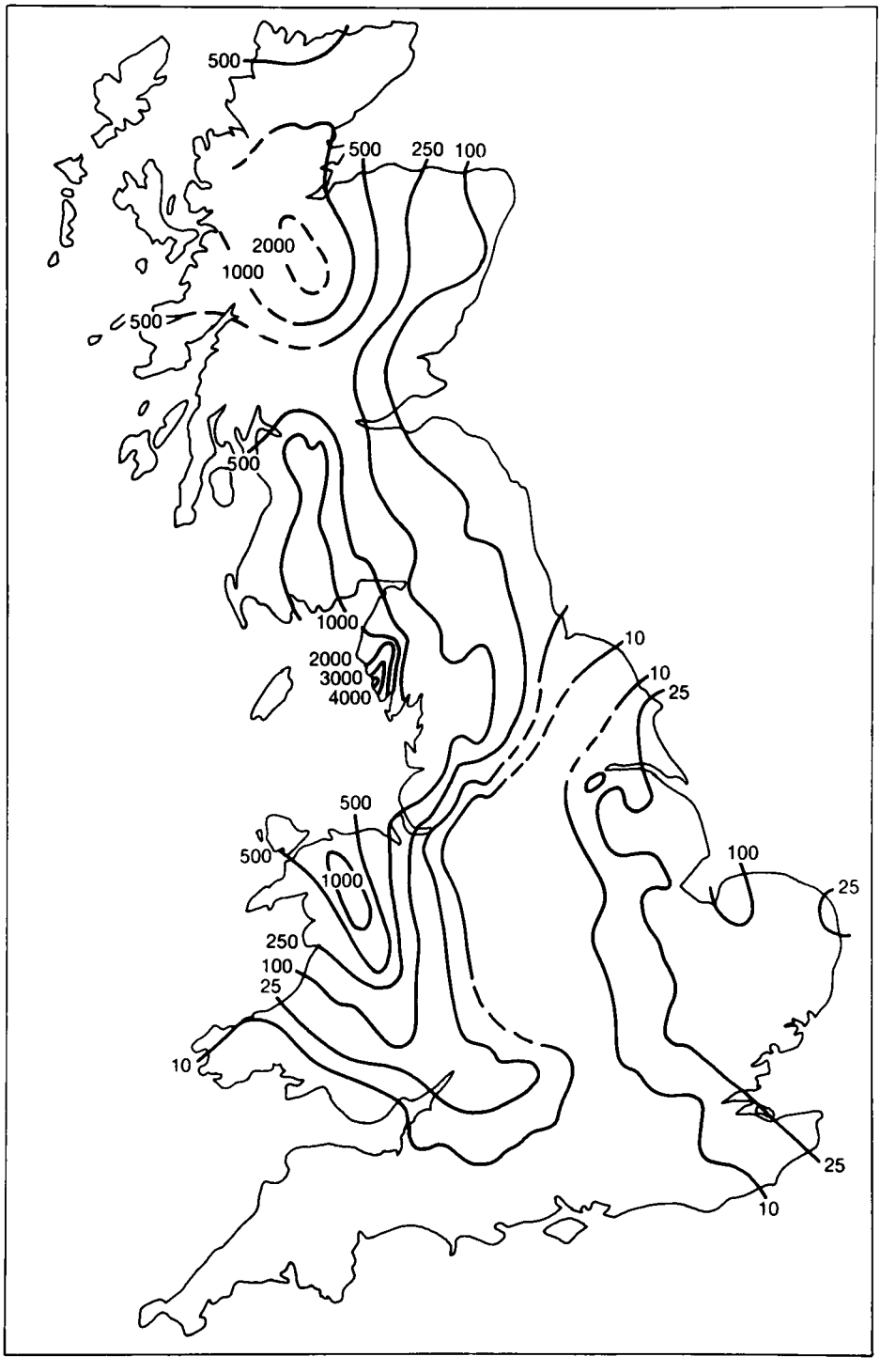


FIGURE 31. Surface depositions of Cs-137 (Bq m^{-2}) on grass as a result of the rain of 3 May based on extensive analyses by the Institute of Terrestrial Ecology.

objectives in mind which are of mutual interest. Their measurements filter through to the Office more slowly; in fact a complete picture for any day, having undergone proper quality control, may not become available for several months.

For most purposes this is quite acceptable, but for nuclear accidents where food monitoring has to be rapidly and accurately aimed, within a day or two, at areas where depositions were highest, this delay is much too great. Moreover, many of these rain-gauges are often sited in the more remote areas of the country, in hilly areas where the rainfall often greatly exceeds the levels in lowland areas. Because of their remoteness, by mutual consent, some of these may not always be read daily over weekends or, in particular, bank holiday weekends. As fate would have it, the Chernobyl plume crossed the country on such a bank holiday weekend! Nevertheless a careful analysis of the available measurements, considered in the light of the moving location of the plume, has led to a detailed and reasonably consistent map of the rainfall as experienced by the plume. This map, previously published by the authors Clark and Smith (1988), is shown in Figure 32. For clarity, rainfall is indicated in rather broad bands as defined in the Figure, which perhaps loses some of the fine detail. The original station-by-station values are retained by the authors who can be consulted for local details wherever necessary.

However it must be remembered that this survey took several months to complete. It should also be noted that in mountainous areas the gauges are more likely to be situated at accessible locations rather than on mountain tops where the rain is usually heavier, and therefore some under-estimation of interpolated rainfall and implied deposition in these areas is likely.

An alternative and certainly a quicker approach is to use the output of rainfall intensity obtained from a network of weather radars. These give intensities with excellent time and space resolution (namely every 15 minutes and over 5 km $\times$ 5 km squares). Whilst the precision may be somewhat affected by a number of factors, for example the shadowing effects of intervening hills, ground clutter and rainfall intensity itself, the qualitative picture is extremely good given sufficient radars, and is available in real time. Even the accuracy can be improved by various techniques such as comparing the output with those surface gauge data that are quickly available. At present England, Wales and Ireland are reasonably well covered by these radars. Plans are now well established to cover Scotland in the next decade. The existing network and the proposed extended network are shown in Figure 33. Similar radar networks are being established, or already exist, in most countries in Europe and their data will be operationally exchanged if current discussions prove successful.

Between Friday 2 May and Sunday 4 May the following 5 radars were in operation: Hameldon Hill, Chenies, Predannack (strictly at its earlier site at Camborne on the other side of the peninsula), Clee Hill, and Dorset (at its previous site of Upavon about 80 km to the north). Thus England, most of Wales and the southern parts of Scotland were well covered. Figure 34 shows the aggregated radar rainfall map for these areas as experienced by the moving Chernobyl plume. Allowing for the quantitative uncertainties touched on above, the agreement with the surface gauge rainfall map is very good. Perhaps the biggest difference is in Snowdonia which was not particularly well covered by the Clee Hill radar due to the intervening hills shadowing the area.

The radar rainfall map was available very shortly after the passage of the plume as soon as a reasonable idea of the plume's movement became available.

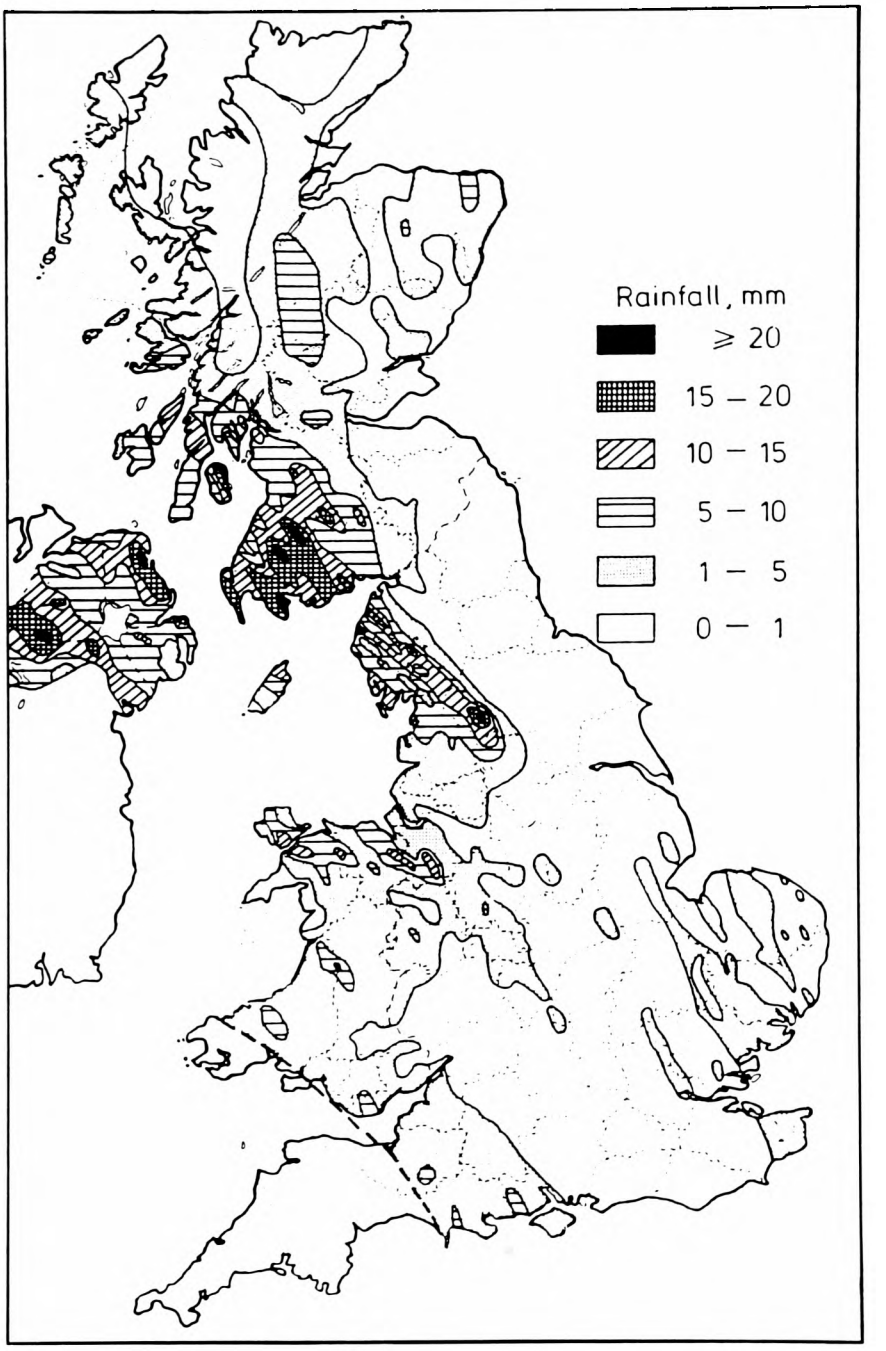


FIGURE 32. The map of rainfall, determined from over 4000 rain-gauge station measurements which intercepted radioactivity in the Chernobyl plume. Rain which did not fall during the time when the plume was overhead is excluded. The dashed line indicates the south-western boundary of the radioactive rainfall.

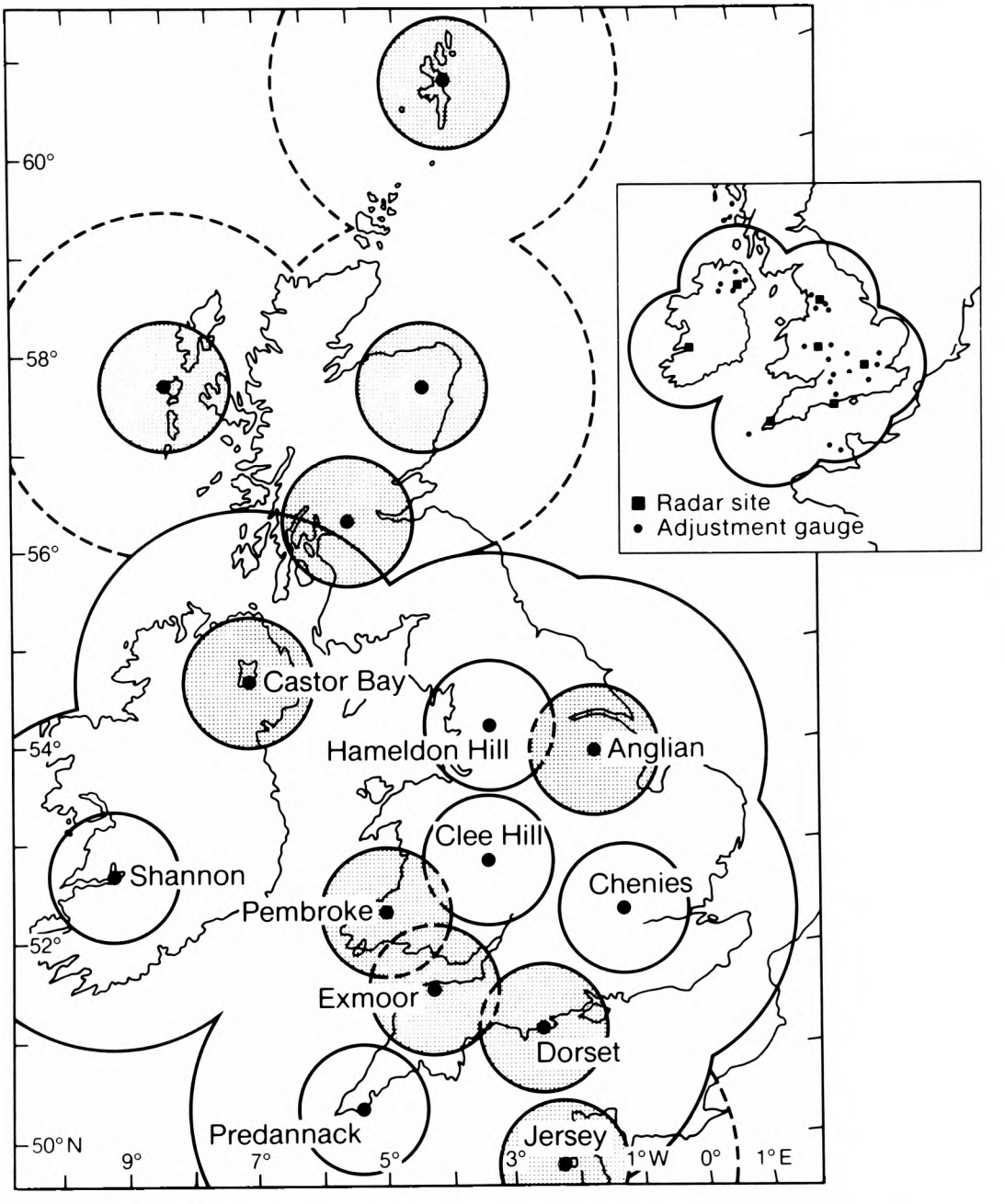
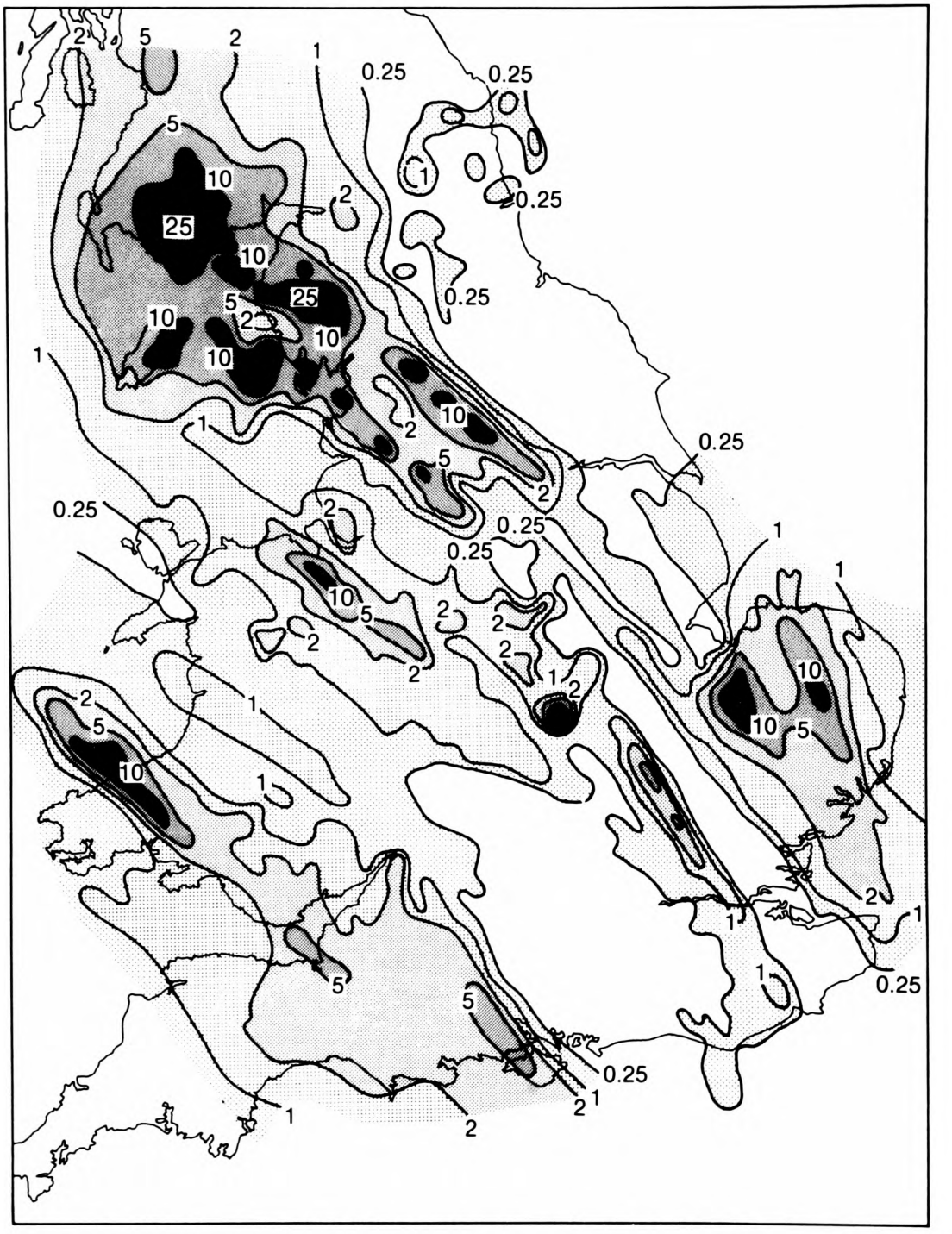


FIGURE 33. The network of weather radars, existing and planned over the United Kingdom and the Republic of Ireland, at the time of the Chernobyl passage. Those with open inner (75 km) circles were in existence and operational; those with hatched circles were not. However two additional radars, not shown here, at Camborne (in Cornwall) and at Upavon (in Wiltshire) were operational at the time, but are being replaced by new radars shown here at nearby Predannack and Dorset respectively. The sites of adjustment gauges used to monitor the radar rainfall are shown in the inset together with weather radar sites.


0.25
0.25
0.25

12. RADIO-NUCLIDE CONCENTRATIONS IN AIR

The three radio-nuclides of greatest radiological significance within the plume were I-131, with a half-life of only 8 days, Cs-134 with a half-life of slightly more than 2 years, and Cs-137 with a half-life of 30.2 years. Both caesium isotopes were almost entirely in particulate form whereas the I-131 was in both gaseous and particulate forms. Cambray *et al.* (1987) give details of measurements made at Harwell during early May in which the gaseous and particulate I-131 components were measured using so-called 'Maypacks' which contain charcoal-loaded filter papers, charcoal beds and glass-fibre filters. Recorded ratios of total to particulate I-131 range from 2 to 4 with the average ratio being about 3. This is confirmed by other measurements (see Cambray *et al.* 1987, Government departments and NRPB 1986, CEGB 1986, Ministry of Agriculture Fisheries and Food 1987, Fry *et al.* 1986, Jackson *et al.* 1987).

Table II gives a compilation of measured concentrations of particulate I-131 and Cs-137 in air taken within the Chernobyl plume. The ratio of the two clearly shows some scatter which may be real or may simply reflect the difficulty in making very precise measurements at these rather low concentrations. Overall the particulate I-131 concentration is just under twice that of the Cs-137.

Combining these air concentrations (for the Cs-137) with the time-duration of the plume overhead yields a map of the approximate time-integrated concentration for the United Kingdom (see Figure 35). Similar maps for particulate and total I-131 can be inferred using the ratios quoted above.

13. DEPOSITION ON GRASS

For radiological protection reasons, most of the deposition data available at an early stage in the United Kingdom referred to depositions on grass (see Cambray *et al.* 1987, Government departments and NRPB 1986), because these could be related to subsequent levels in cows' milk and other foodstuffs (Ministry of Agriculture, Fisheries and Food 1987). The deposition densities on grass measured during 3–6 May 1986 are given in Table III as county averages (Government departments and NRPB 1986). In regions where there was little or no rainfall, the average I-131 to Cs-137 ratio on grass was about 18. This high ratio reflects, and is consistent with, a higher dry deposition velocity for the I-131 vapour than for the Cs-137 and the I-131 particulates, in combination with the higher integrated air concentrations of gaseous and particulate I-131 as discussed in the previous section. In areas where there was light or scattered rainfall, the average I-131/Cs-137 ratio was lower by a factor of 5 and where there was heavy rainfall the ratio decreased to below 2. For example, the ratio on grass was about 4 in south-east England where there was generally only light rainfall with a few isolated thunderstorms giving heavier rainfall during the early hours of Saturday 3 May, as the plume moved northwards. In north-west England and south-west Scotland on the other hand, where there was heavy rainfall during the storms, the ratios observed on grass were directly comparable to the observed ratios of the particulate fractions of the respective species in the air (which, as has been shown, were just less than 2) implying that the gaseous I-131 must have been largely washed off the grass into the soil.

Whilst the depositions quoted in Table III could be used to infer dry deposition velocities, it is preferable to use more carefully defined data in which problems of subsequent wash-off by later rain and of radioactive decay can be avoided. According to Fry (1987) and to

TABLE II. *A compilation of measured concentrations in air (extracted from Government departments and NRPB 1986) taken within the main Chernobyl plume. Note that these measurements refer to particulate components only. Units: Bq m^{-3}.*

Location	Particulate I-131	Cs-137	Ratio	Location average ratio
Berkshire	2.20	1.74	1.26	—
Dorset	0.29	0.15	1.95	—
Dumfries and Galloway	2.70	2.20	1.23	—
"	0.83	0.75	1.11	—
Gloucestershire	2.10	0.66	3.18	
"	1.10	0.48	2.29	..... 2.69
"	0.22	0.13	1.69	
Gwynedd	0.69	0.17	4.06	—
Highlands	1.70	0.90	1.89	—
Kent	3.00	1.80	1.67	
"	2.63	1.95	1.35	
"	6.29	2.54	2.48	
"	0.99	0.66	1.50	..... 1.82
"	8.00	5.00	1.60	
"	3.32	1.37	2.42	
Lothian	0.76	0.50	1.52	—
Oxfordshire	3.03	1.40	2.16	
"	1.43	0.71	2.01	
"	0.83	0.43	1.93	
"	4.20	1.70	2.47	
"	5.32	1.90	2.80	..... 2.28
"	3.18	1.60	1.99	
"	0.50	0.18	2.78	
"	0.60	0.38	1.58	
"	0.96	0.50	1.92	
Strathclyde	2.20	1.41	1.56	
"	0.75	0.45	1.67	
"	0.59	0.32	1.84	..... 1.57
"	0.31	0.27	1.15	
W. Yorkshire	3.00	1.50	2.00	—
Suffolk	6.7	2.7	2.48	—

The average ratio defined as Σ (I-131)/Σ (Cs-137) = 1.93

Cambray *et al.* (1987) the retention half-period is typically only about 5 days. Certain data from Oxfordshire essentially avoid these problems. Two independent measurements of the I-131 content on grass cropped at around 0930 GMT on Saturday morning, 3 May, are available. One gave a deposition of 380 Bq m^{-2}, the other 689 Bq m^{-2}. The disparity between these is a timely reminder of the uncertainties associated with the inference of deposition velocities and indicates the possible influence of other factors, for example the grass length, sheltering effects from nearby obstacles, or errors in analysis. However, taking the average of these two measurements, namely 534.5 Bq m^{-2}, it can be related to the concurrently measured average concentration of particulate I-131 in the air, equal to 0.96 Bq m^{-3}. This reading is quoted in Table II for Oxfordshire. Corresponding measurements for the Cs-137 are a deposition of 16.5 Bq m^{-2} and a concentration of 0.5 Bq m^{-3}.

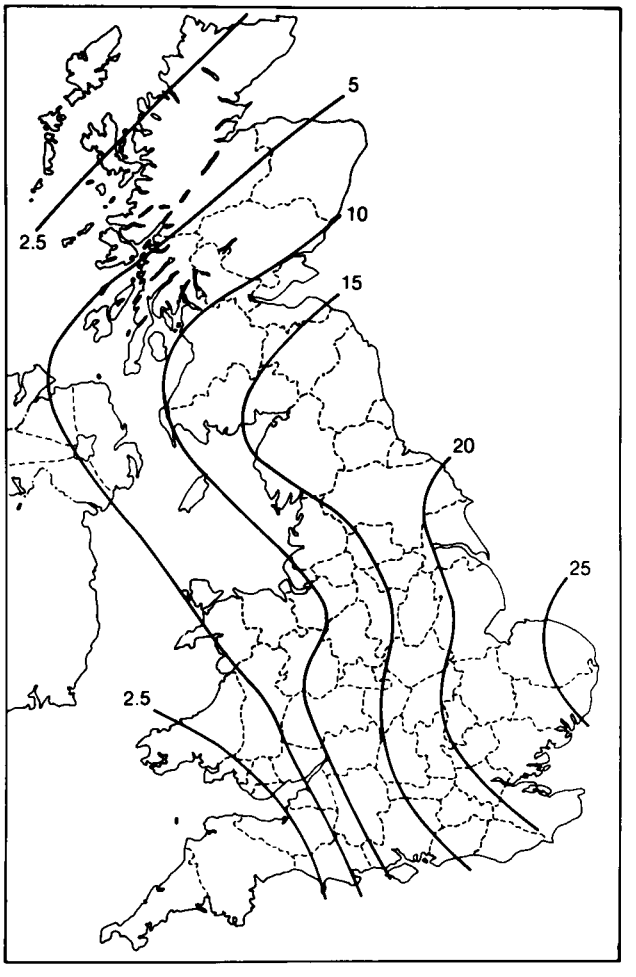


FIGURE 35. Contours of time-integrated concentration of Chernobyl-derived caesium-137 in air (units Bq m^{-3} × hours). County boundaries are shown by dashed lines.

Considering the caesium first, the dry deposition velocity (v_{part}) is therefore given by

$$v_{part} = \frac{16.5 \times 100}{0.5 \times 24 \times 60 \times 60} = 0.038 \text{ cm s}^{-1}.$$

If the same deposition velocity is assumed for the iodine particulates, then v_{gas} for gaseous iodine can be calculated

$$\underset{\substack{\text{(dep) } (v_{part}) \text{ (conc) (time)} \\ \text{particulate contribution}}}{534.5 = 0.00038 \times 0.96 \times 24 \times 60 \times 60} + \underset{\substack{\text{(gas conc) (time)} \\ \text{gaseous contribution}}}{v_{gas} \times 2 \times 0.96 \times 24 \times 60 \times 60}$$

i.e. $v_{gas} = 0.3 \text{ cm s}^{-1}$.

TABLE III. *County averages for deposition densities on grass during the period 3–6 May 1986 (Government departments and NRPB 1986)*

County or Region	Deposition density on grass (Bq m^{-2})		No. of samples	I-131/Cs-137 ratio	Average ratio $\frac{n \times \text{I-131}}{n \times \text{Cs-137}}$
	I-131	Cs-137	(n)	(r)	
Predominantly dry areas					
Berkshire	242	20	5	12	
Channel Islands	151	4	4	38	
Cleveland	70	17	2	4	18
Oxfordshire	459	22	14	21	
Some light rainfall					
Cheshire	325	93	6	3.5	
Dorset	64	25	2	2.6	
Essex	1345	285	1	4.7	3.8
Gloucestershire	1356	351	2	2.9	
Kent	2346	—	1	—	
Lancashire	1327	358	8	3.7	
Predominantly wet areas					
Cumbria	2246	1334	42	1.7	
Dumfries & Galloway	610	598	14	1.0	
Gwynedd	1009	1235	2	0.8	
Highlands	3604	1164	7	3.1	1.8
Orkney	3159	682	4	4.6	
Strathclyde	3445	2285	2	1.5	
West Yorkshire	1259	680	4	1.9	
North Yorkshire	801	470	10	1.7	

These values cover a diurnal cycle, whereas actual deposition velocities may be extremely small at night and perhaps double the above values during the day. They are also consistent with the county average depositions on grass in Table III for Berkshire and Oxfordshire since, according to Figure 35, the integrated time concentration for Cs-137 was about 16 Bq m^{-3}h, implying a deposition of 21.9 Bq m^{-2} for Cs-137 and 396 Bq m^{-2} for I-131, close to the measured values of 16.5 and 534 Bq m^{-2} respectively.

14. TOTAL SURFACE DRY DEPOSITION

From previous studies by Chamberlain and Chadwick (1966) it is known that only a proportion (f) of the total dry deposition to the surface is actually retained on the vegetation. The factor, f, depends principally on the weight of the vegetation per unit surface area. The rest is taken up by the soil. Chamberlain and Chadwick concluded that for grass the fraction retained is given approximately by

$$f = 1 - \exp(-2.78\, w)$$

where w is the weight of grass per unit area, in kg m^{-2}. Data in support of this relationship are given in their paper and the goodness of fit is demonstrated in a plot which is reproduced here as Figure 36.

British Nuclear Fuels Ltd (BNFL) made many measurements of w during the period of interest at their site in Cheshire. These can be inferred from published data (Government departments and NRPB 1986) on I-131 deposition on grass expressed both in terms of Bq m^{-2} and Bq kg^{-1}. The implied values of f range from 0.75 to 0.91 with an average of 0.84. A single value from Somerset of 0.88 confirms this and suggests that a similar value may be appropriate for Harwell.

With $f = 0.84$, the Harwell measurements, used above, imply total dry depositions to the surface were 19.6 Bq m^{-2} for Cs-137 and 636.3 Bq m^{-2} for I-131. Dry deposition velocities should also be increased to give

$$v_{part} = 0.046 \text{ cm s}^{-1} \quad \text{(particulates)}$$
$$v_{gas} = 0.36 \text{ cm s}^{-1} \quad \text{(gas)}.$$

These values are consistent with those made by Chamberlain (1960) after the Windscale accident in 1957.

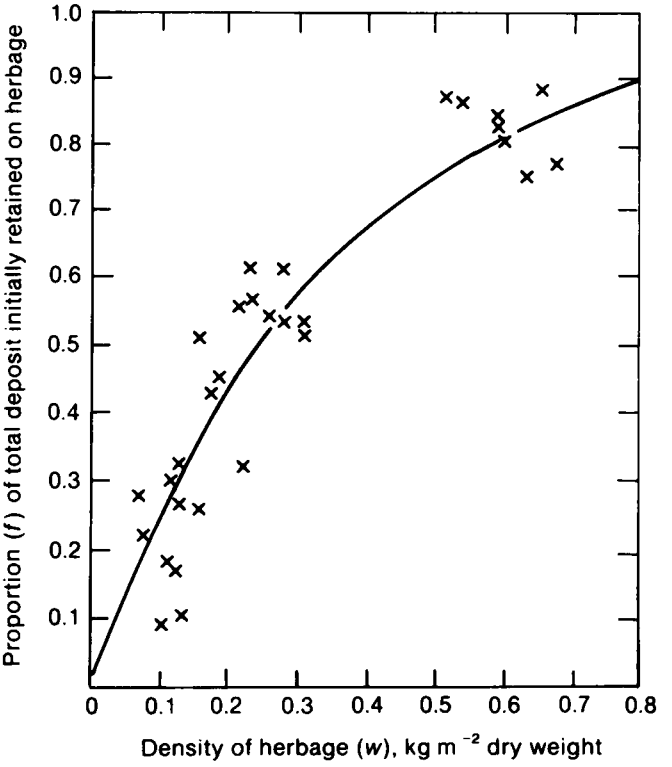


FIGURE 36. Deposition of radio-iodine vapour on grassland; the crosses are from a field experiment (Harwell). The curve represents a theoretical fit to the data devised by Chamberlain (1960).

When rain falls, either during the passage of the airborne activity or between the passage and the time of sampling, more of the activity is found washed down into the soil. This seems to be particularly true for the gaseous components, especially if they are water soluble. As noted earlier, this is seen from Table III where in very wet areas the ratio of I-131 to Cs-137 is virtually equal to the ratio of the airborne particulate concentrations. Hence grass sampling taken after rain is always likely to lead to a gross underestimation of the total deposition, but of course retains important validity in respect of the amount of activity likely to be ingested by grazing animals at that time.

The Institute of Terrestrial Ecology at Merlewood has also carried out a very extensive survey of Cs-137 depositions on grass across the country and has compiled the map shown in Figure 31. This map confirms the importance of wash-off by rain in the levels retained on vegetation.

15. WET DEPOSITION

The wet deposition W of radio-nuclides depends on the interception of the plume by rainfall. This rainfall has already been described in some detail for the passage of the Chernobyl plume in an earlier section. For many areas, especially in Wales, north-west England, Ulster and south-west Scotland, the rainfall was quite heavy, and in these areas wet deposition totally dominated dry deposition.

Estimation of wet deposition is in principle a very complex matter involving the macro- and micro-physics of clouds as well as the physical and chemical properties of the radio-nuclides involved. An excellent description of these problems is given by Slinn (1984).

Nevertheless approximate relationships can be inferred from measurements which seem appropriate for the study of wet deposition from Chernobyl.

If R = rainfall in metres,
C = the average concentration of any specified nuclide in the air in Bq m^{-3} during the rain,
W = the wet deposition of that nuclide on the underlying surface in Bq m^{-2} resulting from the rainfall, and
K = the average concentration in the rain in Bq m^{-3} of actual rainwater

then the ratio w_r of K/C appears to be virtually independent of C over a range of four orders of magnitude (see Figure 37). Since $W = RK$ it follows that

$$W = w_r CR.$$

Figure 37 indicates a variation of around a factor of 3 in the average value of w_r which may be due to real physical variations in the physics of the clouds and the rain involved or to errors in measurements or to both. Evidence from parallel studies in the acid-rain problem suggests that w_r should depend on rainfall intensity, especially for particulate nuclides for the reasons already given. Whilst this explanation ignores coalescence in the formation of the larger droplets it nevertheless points to some possible inverse relationship between w_r and rainfall intensity.

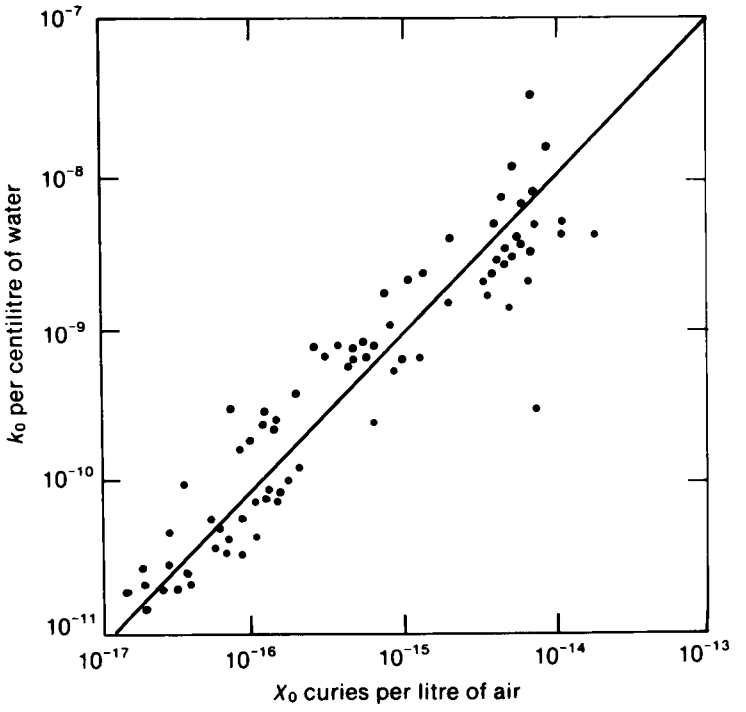


FIGURE 37. An example of the correlation between measured concentrations of total fission products in precipitation, k_0, and their concentrations in surface-level air, χ_0. Notice that the best fit for the washout ratio, viz., $w_r = (k/\chi)_0 = (1.0 \pm 0.3) \times 10^6$, appears equally adequate over 4 orders of magnitude of variation in k and χ, (based on Gedeonov *et al.* 1970).

While bearing these points in mind, the simple relation

$$W = w_r CR$$

will be used as the basis for analysing the wet deposition from the Chernobyl plume.

An interception factor (f_i) can be introduced into the equation to allow for the differing abilities of surfaces to intercept washout material, in direct parallel with the interception of dry deposition. For soil, f_i can be assumed to be 1, but for grass the factor can vary from 0.05 to 0.3 (Chamberlain 1970, Simmonds *et al.* 1979, Fulker 1987). An analysis of the available monitoring data indicates that the product, $w_r f_i$, for deposition of I-131 and Cs-137 on grass is of the order of 10^5, if we use particulate air concentrations and rainfall data for 2–4 May 1986. For example, in Cumbria the average rainfall during the passage of the plume was about 10 mm, and assuming an average particulate air concentration of 1 Bq m^{-3} for I-131 and 0.5 Bq m^{-3} for Cs-137 during rainfall, it is found that the observed average deposition densities on grass in Table III of 2.2 kBq m^{-2} and 1.3 kBq m^{-2} respectively imply that $w_r f_i$ was over 2×10^5. If the same assumptions are made for Dumfries and Galloway, the observed average deposition densities on grass imply values for $w_r f_i$ less than 1×10^5. These calculations show the potential uncertainties in using aggregated grass monitoring data to

estimate washout. The data came from a number of laboratories, and no allowance has been made for different types and qualities of grass nor for other variables. For example, although the grass measurements in Table III were made soon after the passage of the plume, some losses will already have occurred (Cambray *et al.* 1987, Fry 1987). Despite these reservations, early grass measurements avoid the need to correct for weapons fall-out, and variations due to surface water run-off and drainage are likely to be small compared to later soil measurements. We therefore assume a value of 1.5×10^5 for $w_r f_i$ on grass but, recognizing that retention on grass varies significantly, there will be an uncertainty of at least a factor of 2.

16. TOTAL SURFACE WET DEPOSITION

To determine w_r, simultaneous measurements of concentration in air and in rain, or of total deposition, are required. Unfortunately such combinations are very rarely available from the published data records. Cambray *et al* (1987) have published measured values of total deposition of I-131, Cs-137 and Cs-134, made within a month of the plume passage and subsequently corrected for decay back to 3 May. From measurements of the concentration of Cs-137 and Cs-134 in rain made during and soon after the passage, the ratio (Cs-134/Cs-137) of the two isotopes appears to be fairly constant at around 0.6. Because of levels of Cs-137 still in the soil originating from the nuclear weapon tests in the late 1950s and early 1960s, the Cs-137 originating from Chernobyl in the measurements of Cambray *et al.* (1987) is best inferred from the Cs-134 measurements appropriately modified by the 'rain-ratio' of 0.6. (The weapon tests gave virtually no Cs-134 and what there was would have decayed into insignificance by 1986.)

Table IV gives an extract of the early measurements from Cambray *et al.* (1987) with the Cs-137 so inferred from the Cs-134 data. The average ratio of I-131 to Cs-137 turns out to be just less than 5, reasonably consistent with, but slightly less than, the ratio of airborne concentrations discussed earlier. The small inconsistency can be explained in terms of a slightly smaller washout factor for gaseous I-131 than for the particulates.

Taking four of the stations for which reasonable estimates of the appropriate rainfall and concentrations in the air can be given, values of w_r can be deduced (see Table V). Whilst there is scatter in these values, the average $w_r = 6.5 \times 10^5$ is encouragingly consistent both with the value used for sulphate aerosol in modelling studies of acid rain (7×10^5) and with values obtained by Cawse (1974) at Chilton in 1973 from studies of the washout of Cs-137 in frontal rain (the caesium having originated from the weapon tests) in which he found $w_r = 5.5 \times 10^5$ (see Slinn 1984).

Using the washout factor of 6.5×10^5 and interpolated concentrations in air, we can estimate the total deposition of Cs-137 at each of the 4000 rain-gauge stations throughout the United Kingdom (Clark and Smith 1988). The airborne concentrations during rain were obtained from the contours in Figure 38. The resulting spot depositions have in turn been interpolated to give the contours shown in Figure 39. Radar measurements at the time showed narrow bands of rain moving across the country, and this concept was later supported by the gauge data. Where these rainbands intercepted the Chernobyl plume, radio-nuclide deposition would also have occurred in narrow bands. More detailed contours for south-west Scotland and Cumbria are given in Figure 40 with measurements of Cs-137 in soil provided by Cambray, Fulker, Appleby and McDonald (personal communications). There is good general agreement although some caution is required when

TABLE IV. *Measured values of total deposition of iodine-131 and caesium-137. The caesium values have been corrected for pre-Chernobyl soil contents derived from the fall-out from atomic bomb tests in the 1950s and 1960s. The data are from AERE (Cambray et al. 1987). Units are 1000 Bq m^{-2}.*

Location	I-131	Cs-137	I/Cs ratio
Lerwick	27.0	4.60	5.87
Dounreay	5.7	1.25	4.56
Forsinard	5.5	1.04	5.29
Eskdalemuir	4.7	0.82	5.73
Kinniside (Cumbria)	14.0	3.90	3.59
Ill Bell "	19.0	2.40	7.92
Wasdale "	12.4	2.90	4.28
Holmrook "	41.0	10.00	4.10
Trawsfynydd, N. Wales	7.9	1.85	4.27

"average" ratio = Σ I/Σ Cs = 4.77

Taking a selection of 4 of these sites, we obtain the following Table V.

TABLE V. *Estimates of the scavenging ratio*

Location	Chernobyl total dep. Cs-137 (Bq m^{-2})	Estimated rainfall (mm)	Air conc. Bq m^{-3}	Implied w_r
Holmrook	10 000	Storm 1: 5	3	5.88×10^5
		Storm 2: 2	1	
Lerwick	4 600	4	2$^+$	5.75×10^5
Dounreay	1 250	2.5	0.7	7.14×10^5
Trawsfynydd	1 850	2	1.2	7.71×10^5

Average implied $w_r = 6.50 \times 10^5$

Note: $^+$ Estimated.

interpreting the results. As mentioned earlier, rain-gauge stations are normally in accessible places below the highest land and can therefore underestimate rainfall in mountainous areas. Furthermore, measurements of deposition are not normally coincident with rain-gauge stations, and rainfall can vary over relatively short distances. The amount of Cs-137 in soil also varies over short distances, as exemplified by Fulker's measurements in Cumbria (Jackson *et al.* 1987, Fulker 1987, and Fulker personal communication) in which results varied from 1.8 to 8.8 kBq m^{-2} at one location and from 5 to 11.7 kBq m^{-2} at another. Variations in altitude, drainage, soil type and land usage contribute to this.

Turning to the I-131, the washout factor for the gaseous component may be different from that for the particulates. If the latter is assumed equal to the caesium value of 6.5×10^5, then the former may be inferred from the average ratio of I-131 to total Cs-137 already seen in

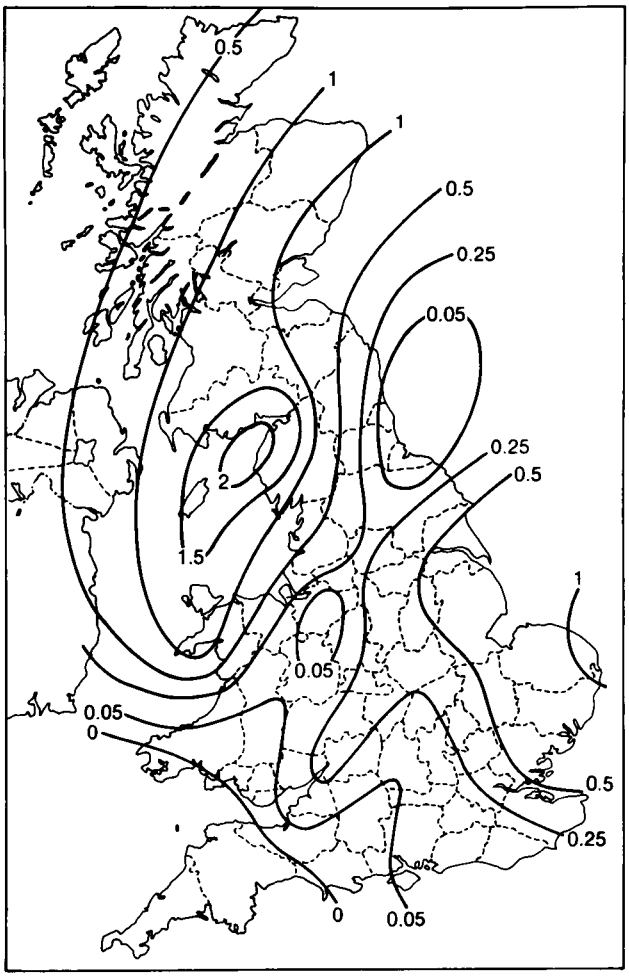


FIGURE 38. Contours of average concentration (Bq m^{-3}) of caesium-137 in air during rainfall. County boundaries are shown by dashed lines.

Table IV for measured depositions in soil, and from a very similar ratio, equal to 5.16, obtained from rather more scattered measurements of concentration in rain collected over periods fully extending over the passage of the plume (Table VI). Taking the overall average ratio of 5, a ratio of particulate I-131 to Cs-137 equal to 2, and of total I-131 to gaseous iodine equal to 3, simple algebra shows that

$$w_r \text{ (gaseous I-131)} = 0.75\ w_r \text{ (particulate Cs-137)}$$

i.e. w_r (gaseous I-131) $= 4.9 \times 10^5$.

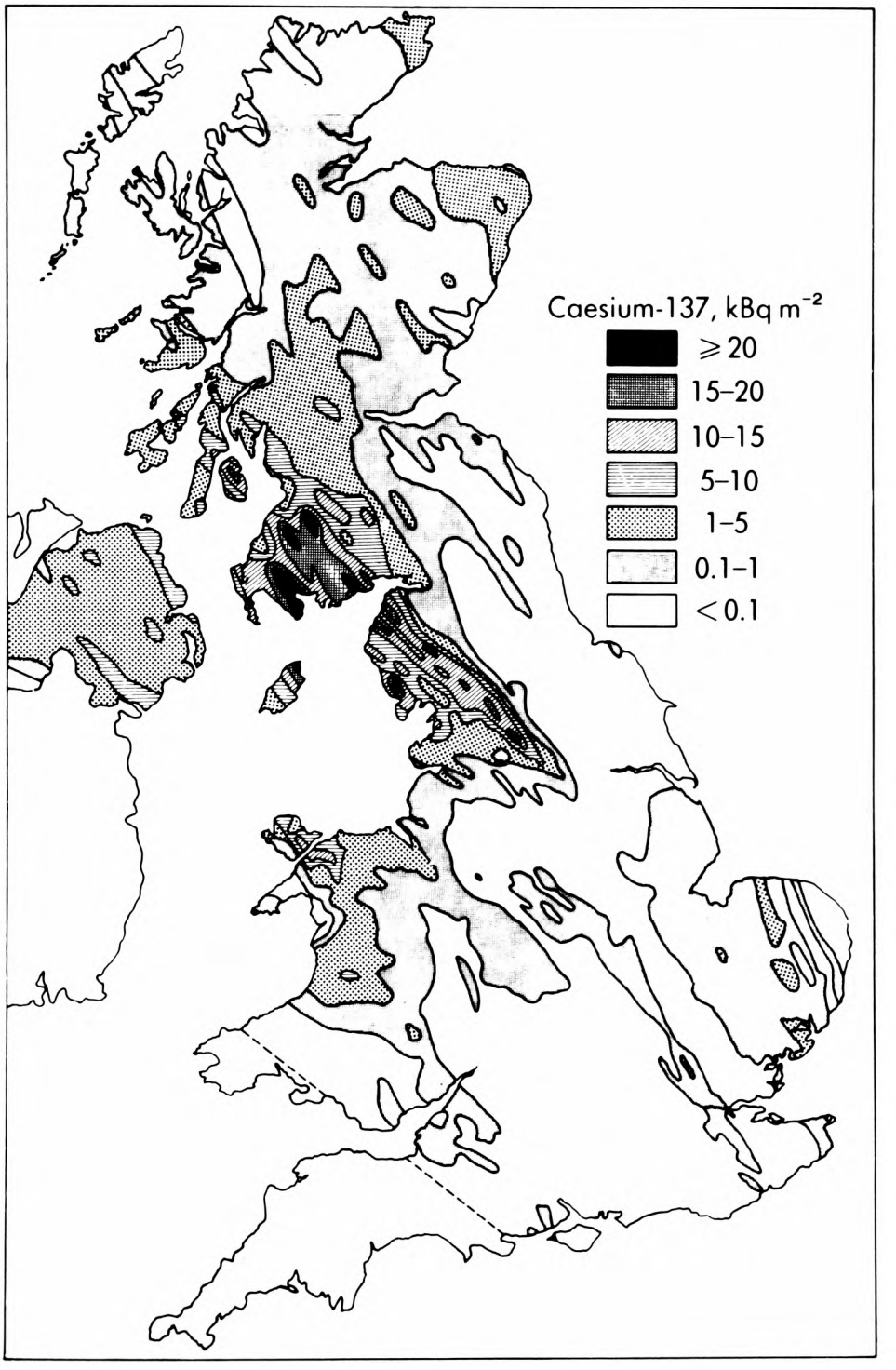


FIGURE 39. Contours of empirically derived total depositions of caesium-137, from Chernobyl, over the United Kingdom. Units are kBq m^{-2}.

TABLE VI. *Depositions in rain (Bq m^{-2}) inferred from concentrations and rainfall (data from Cambray et al., 1987). Values are inferred from analyses of rainwater collected over periods extending over the full passage of the Chernobyl plume.*

Location	I/Cs ratio	
Aldergrove	5.95	
Conlig (Northern Ireland)	3.23	
Lerwick	5.42	Average deposition-weighted
Eskdalemuir	14.38	ratio = 5.16
Dounreay	31.92	
Snowdon	3.33	

17. TOTAL DEPOSITION ON THE UNITED KINGDOM

It is possible to estimate the total amount of Cs-137 and I-131 deposited on the United Kingdom from Chernobyl using the dry deposition velocities and washout factors derived above. The average integrated air concentration for Cs-137 was about 15 Bq m^{-3} h in the United Kingdom (see Figure 35). This gives an average dry deposition of 27 Bq m^{-2} if a dry deposition velocity of 5×10^{-4} m s^{-1} is used. The average total wet deposition on the ground is estimated at 1300 Bq m^{-2} if the washout factor of 6.5×10^5 is used and an average air concentration of 1 Bq m^{-3} during rainfall with an average rainfall of 2 mm for the United Kingdom. The average total deposition density was therefore about 1.3 kBq m^{-2}, and the total deposition of Cs-137 on the United Kingdom (area 2.5×10^{11} m^2) about 3×10^{14} Bq. These rough estimates are supported by an integration of the deposition values given in Figure 39, which yields 1.2 kBq m^{-2} and are in agreement with Cambray's estimate of 3.2×10^{14} Bq for total deposition on the United Kingdom (Cambray *et al.* 1987).

The total deposition of I-131 from Chernobyl was considerably more complicated because of its relatively high dry-deposition velocity and the presence of both vapour phase and particulate iodine species in the plume. Reported values for I-131 in the top 5 cm of soil, including grass, show I-131 to Cs-137 ratios of about 5:1 in the predominantly wet areas (Cambray *et al.* 1987, Fulker 1987, Fulker personal communication). This is confirmed as we have seen by measured ratios in rain. These observations imply that the total deposition of I-131 on the United Kingdom must have been at least 1.5×10^{15} Bq and, allowing for its high dry deposition velocity relative to Cs-137, we estimate the total deposition might have approached 2×10^{15}.

As a percentage of the total releases from the Chernobyl reactor, the amounts of I-131 and Cs-137 deposited on the United Kingdom were about 0.7% and 0.8% respectively, based on Soviet estimates of 3×10^{17} Bq and 4×10^{16} Bq for the total releases (IAEA 1986). These percentages are uncertain by at least a factor of 2, and if Cambray's estimate of 5×10^{16} Bq for the total Cs-137 release is used (Cambray *et al.* 1987), the percentage of Cs-137 deposited on the United Kingdom becomes 0.6%. An analysis of the trajectories of the plume indicates that the part of the release affecting the United Kingdom left Chernobyl during a two-hour slot on Saturday 26 April, and the Soviet authorities estimate that, on that first day, about 10^{17} Bq of I-131 and 10^{16} Bq of Cs-137 were released (Table I). The corresponding percentage of this release affecting the United Kingdom was approximately 2% for the I-131 and 3% for the Cs-137, if we use the average total depositions derived above. The fraction of the I-131 deposited on the United Kingdom was less than that for the Cs-137 because of its short half-life and its higher dry deposition *en route*.

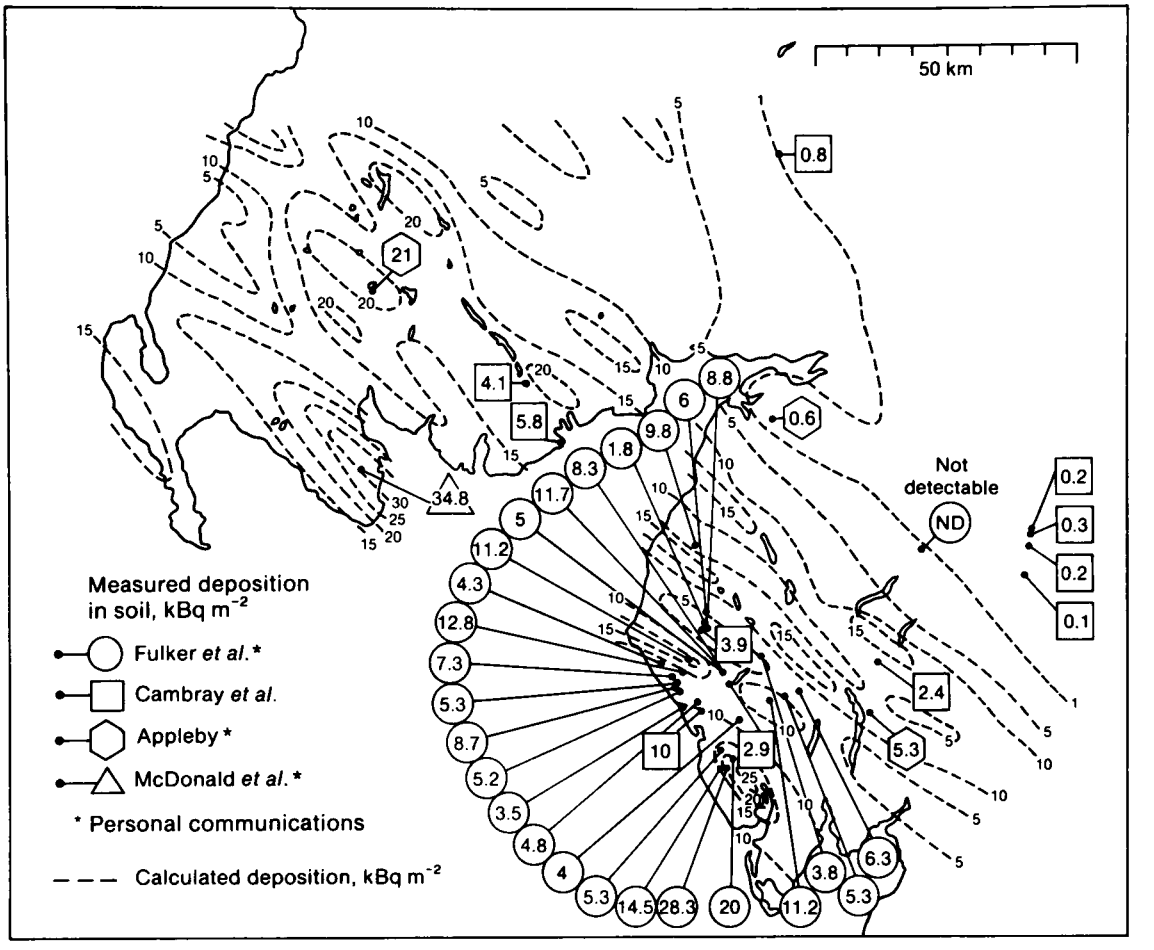


FIGURE 40. A comparison of measured depositions of caesium-137 with the empirically derived depositions for Cumbria and south-west Scotland. The comparison is encouragingly good, taking into account the sizeable small-scale variability shown in some of the measured values taken at the same site. This variability may be due to very local features such as variable drainage, slopes, stones, vegetation, etc.

18. LEVELS OBSERVED IN COWS' MILK

The deposition of I-131 and Cs-137 led directly to incorporation in the human food-chain, and average levels observed in cows' milk in UK counties and regions during 5–8 May are given in Table VII and also in Figure 41 (Clark and Smith 1988, Government departments and NRPB 1986, Ministry of Agriculture, Fisheries and Food 1987). The concentrations of I-131 in milk in parts of southern England were comparable to levels observed in Cumbria and other high-rainfall areas of the north-west, but were not accompanied by similar levels of Cs-137. The levels in milk should reflect deposition on pasture, and Table III also shows that levels of I-131 on grass in Kent and Essex were comparable with the north-west,

TABLE VII. *Average values of I-131 and Cs-137 levels in cows' milk during 5–8 May 1986 (Government departments and NRPB 1986, Ministry of Agriculture, Fisheries and Food 1987)*

County or Region	Radio-nuclides in cows' milk 5–8 May, Bq l^{-1}		
	I-131	Cs-137	No. of samples
Antrim	88	58	7
Antrim and Derry	110	100	3
Avon	20	—	15
Bedfordshire	28	3	2
Berkshire	38	2	5
Channel Islands	19	1	7
Cambridgeshire	66	10	8
Cheshire	11	14	7
Cleveland	14	—	2
Clwyd	27	70	5
Cornwall	5	1	11
Cumbria	110	128	68
Derbyshire	80	—	4
Devon	9	1	13
Dorset	52	4	10
Down	108	79	3
Dumfries and Galloway	151	171	25
Durham	10	10	11
Dyfed	13	14	11
Essex	71	18	19
Fermanagh and Tyrone	166	64	1
Fife	27	13	4
Gloucestershire	34	7	22
Grampian	9	7	4
Greater London	37	—	3
Gwent	15	16	5
Gwynedd	74	124	23
Hampshire	55	6	19
Hereford and Worcester	83	13	11
Hertfordshire	34	5	6
Highlands	61	24	14
Humberside	55	40	12
Isle of Man	159	184	5

whereas Cs-137 levels were low. Wilkins *et al.* (1988) has shown that transfer factors in the milk pathway vary in different parts of the country depending on agricultural practices, but monitoring data for other foodstuffs and environmental materials show similarly elevated I-131 levels in parts of the south, and so dry deposition seems to be the most likely cause here. The densities of I-131 on grass in the areas that experienced little or no rain were of the order of 2 kBq m^{-2} or less, most of which was dry deposited and retained on grass. In areas where there was substantial rainfall during the passage of the Chernobyl plume, total I-131 deposition was much higher, but a smaller fraction appears to have been retained on grass. For example, measurements of total I-131 deposition in the top 5 cm of soil have been reported in the range 10–40 kBq m^{-2} in Cumbria (Cambray *et al.* 1987, Jackson *et al.* 1987),

TABLE VII (cont'd). *Average values of I-131 and Cs-137 levels in cows' milk during 5–8 May 1986 (Government departments and NRPB 1986, Ministry of Agriculture, Fisheries and Food 1987)*

County or Region	Radio-nuclides in cows' milk 5–8 May, Bq l^{-1}		
	I-131	Cs-137	No. of samples
Kent	82	10	25
Lancashire	49	48	23
Lincolnshire	47	13	5
Lothian	72	44	8
Mid Glamorgan	15	14	5
North Yorkshire	31	18	22
Norfolk	125	26	6
Northamptonshire	42	10	13
Northumberland	53	27	10
Nottinghamshire	63	—	6
Orkneys	127	71	16
Oxfordshire	37	13	6
Powys	44	36	13
South Glamorgan	17	16	3
South Yorkshire	45	13	1
Shetlands	3	1	4
Shropshire	11	15	6
Somerset	21	2	29
Strathclyde	61	68	38
Suffolk	59	—	2
Surrey	45	3	4
Tyne and Wear	15	17	2
West Glamorgan	24	18	4
West Sussex	52	4	4
Warwickshire	126	—	4
Wiltshire	32	—	4

where measurements on grass were typically 4 kBq m^{-2} or less (Government departments and NRPB 1986, Ministry of Agriculture, Fisheries and Food 1987). In contrast, Cs-137 deposition in dry areas was low because of its low dry-deposition velocity, but there was significant wet deposition in the higher rainfall areas. The difference between observed levels of Cs-137 on grass, in foodstuffs and in other environmental materials in wet and dry areas, is therefore much more evident, as demonstrated by the cows' milk data shown in Figure 41(b). These observations confirm that dry deposition of I-131 can also contribute significantly to levels in the food-chain.

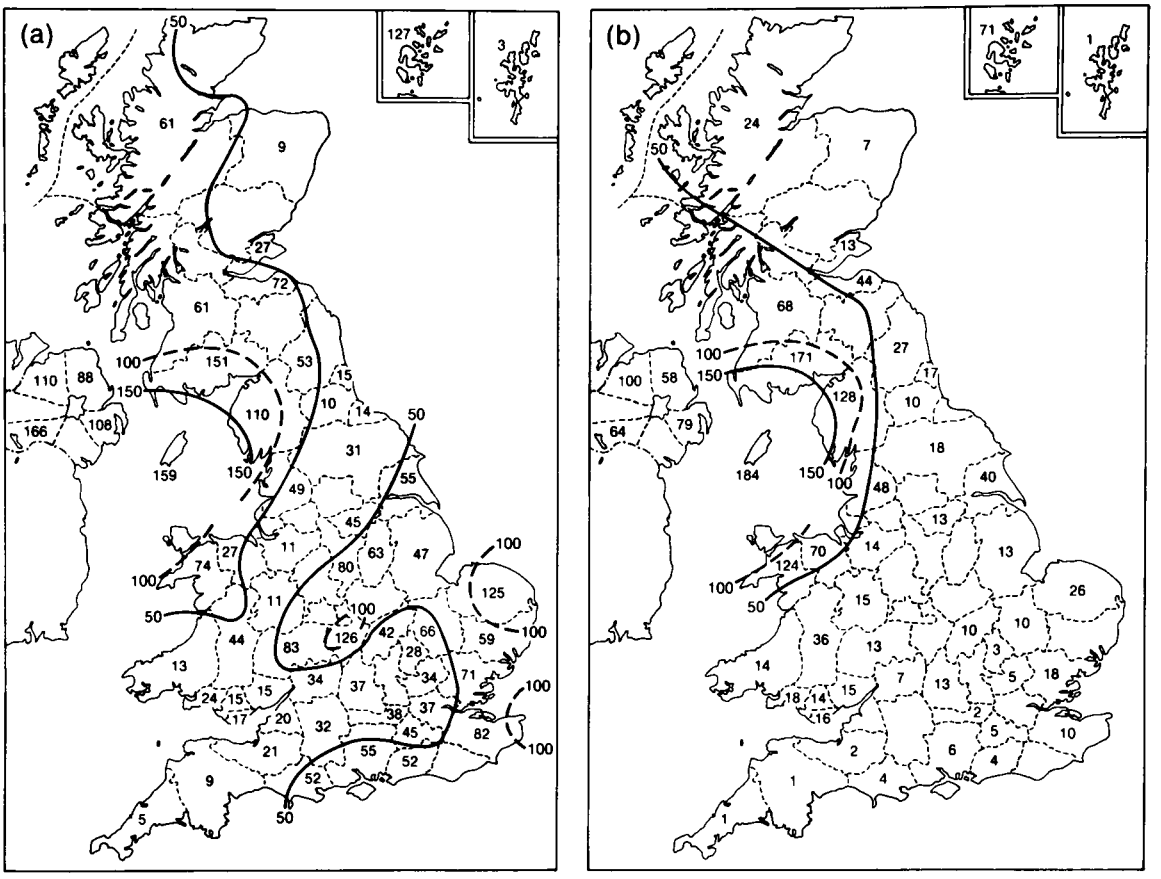


FIGURE 41. Average concentrations (Bq l^{-1}) of (a) iodine-131 and (b) caesium-137 in cows' milk, 5–8 May 1986.

19. LONGER-TERM AGRICULTURAL EFFECTS

As has been seen, the heaviest depositions of Cs-137 occurred in hilly areas of the United Kingdom where sheep farming is the only effective agricultural pursuit. By June 1986, only a few weeks after the plume passage, levels of caesium activity in sheep in some of the worst affected areas had risen sufficiently such that some of the animals exceeded the action level of 1000 Bq kg^{-1}, and restrictions had to be imposed by the Government on their sale, movement and slaughter. At first it was commonly thought that levels would soon drop as the caesium leached away, but this did not happen everywhere. Even 2 years after the event, levels remain sufficiently high for continued restrictions in some areas, whereas in others the fall-off has been much more rapid. The reasons for this are complex and can only be touched upon here very briefly. The important element appears to be the nature of the soil; soils rich in clay minerals rapidly lock-in the free caesium so that it becomes unavailable to the vegetation, whilst poor acidic soils, as commonly found in upland areas of the United Kingdom, are unable to do this effectively with the result that the caesium cycles through the

uppermost humic layers of the soil and the vegetation, and its availability to the grazing sheep falls off only very slowly. The local character of soils has been well studied and documented by various institutes in the United Kingdom, for example by the Soil Survey of England and Wales, and by the Macaulay Institute in Scotland. These Institutes have prepared detailed maps which can be used in principle to predict the longer-term trends in caesium levels. However, details of such predictions are a matter of ongoing research by appropriate organizations, since clearly many complex factors are likely to be involved.

At its simplest level, a rough division of soil types can be made into mineral-rich and acidic mineral-poor soils with the latter acting as an indicator as to where longer-term effects might be experienced. One redeeming feature seems to be that the levels of contamination in sheep fall very rapidly once the animals are taken off contaminated pastureland.

20. CONCLUSIONS

The experience gained from the behaviour of the radioactivity released from Chernobyl into the atmosphere and subsequently deposited on to the surface is proving invaluable in the preparation of models, monitoring networks and other procedures for use should another major accident ever occur in the future.

This perspective can be briefly summarized through a listing of so-called 'conclusions'. These conclusions can be subdivided into three categories, as far as the subject matter of this Report is concerned. Category 1 (20.1.) refers to aspects of the transport and dispersion of the plume, Category 2 (20.2.) to aspects of the deposition and Category 3 (20.3.) to the transfer of radioactivity into the food-chain.

20.1. *Transport and dispersion*

20.1.1. *Synoptic-scale deformation.* Close to the source, the plume behaves very much like conventional plumes from factory chimneys, growing under the action of three-dimensionsal boundary-layer turbulence in a quasi-conical manner. When the width of the plume exceeds one or two hundred kilometres, the synoptic variations of velocity become dominant and the plume grows through deformation as described by Gifford (1987).

20.1.2. *Windshear in the vertical.* Changes of wind speed and direction with height through the plume are a principal factor in diluting the concentration within the plume, especially when deformation is the main mechanism for plume development. Dilution occurs when shear is coupled with vertical mixing, either concurrently or successively through a diurnal cycle.

20.1.3. *Plume correction by radiological data.* Although it appears trajectory analyses carried out by most Centres during and immediately after the Chernobyl accident were reasonably successful in predicting the speed of the debris over Europe, it is almost certain that individual trajectories starting from Chernobyl at the same time differed significantly, and the apparent success is largely a result of the very variable meteorological situation during the whole release. In other circumstances, differences might be much more obvious, and in this case, radiological reports of activity would be invaluable in optimizing the information the models are capable of giving.

20.2. *Deposition*

20.2.1. *Atmospheric stability at the source.* Large releases will usually be hot releases and much of the airborne debris will rise away from the surface. Its vertical profile will depend critically on the stability of the atmosphere, and this will have consequences for the subsequent transport and deposition of the material. Even at the source, a stably stratified surface layer can have a considerable influence on the local deposition of particulates of differing diameters and on the magnitude of the exposure suffered by the local population.

20.2.2. *Deposition rates for differing species.* Although most radiological species will be effectively washed out by precipitation, the rates will differ significantly from one species to another. Dry deposition rates vary very much more with species. Measurements over the United Kingdom confirmed that reactive gases like I-131 dry deposit an order of magnitude faster than particulates (like Cs-137) in the micron or sub-micron range. These differing rates need to be well specified.

20.2.3. *Convective rainfall and deposition shows banded structure.* Rainfall tends to be quite spatially variable and depends on the nature of the precipitating clouds and on the underlying topography. Much of the rain affecting the Chernobyl plume over the United Kingdom came from deep convective storms. These left narrow footprints of rainfall elongated alongwind, with similar footprints of activity-deposition. Interpolation between measurements of Cs-137 (for example) on grass or in soil should therefore be carried out with strong alongwind weighting and not with simple circular weighting.

20.3. *Transfer to foodstuffs*

20.3.1. *The importance of wet deposition.* Precipitation, if it occurs, is very much more efficient than dry deposition at depositing material on the ground where it can affect agriculture. Agriculturists wishing to monitor the levels of deposition rapidly, following the passage of airborne debris, should therefore concentrate in the initial stages on those areas where significant rain intercepted the debris. Information on where this rain occurred can be obtained quickly from operational weather radar, as long as a rough idea of the timing of the plume's movement is available.

20.3.2. *Retention on vegetation.* In areas where little or no rain occurs, most of the deposition will be dry deposition and a high percentage will be retained on the vegetation where it may be ingested by grazing animals. When significant rain falls either during the passage or in the following few days, the retention on the vegetation may be only 0.1–0.25 of the total deposition for particulates, and very small indeed for the gases.

20.3.3. *Levels of I-131 in milk.* If cows are allowed to graze contaminated pastures in the days following the passage of the plume, the levels of I-131 in their milk will reflect the levels on the vegetation.

Although levels will tend to be highest in those areas with large wet deposition, levels in comparatively 'dry' areas may not be dramatically smaller because of iodine's relatively high dry-deposition velocity and because of 20.3.2. above.

20.3.4. *Influence of soil type on long-term effects.* Soil type can critically influence the duration of the continued contamination of foodstuffs and grazing animals.

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